AD/A-004 016

ANALYSIS OF FACTORS AFFECTING TURBINE ENGINE RELIABILITY

K. G. Rummel

Boeing Vertol Company

Prepared for:

Army Air Mobility Research and Development Laboratory

November 1974

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER USAAMRDL-TR-74-82	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD/A-004 646
4. TITLE (and Subtitle) ANALYSIS OF FACTORS AFFECTING TURBINE ENGINE RELIABILITY		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER D210-10912-1
7. AUTHOR(s) K. G. Rummel M. Byrne		8. CONTRACT OR GRANT NUMBER(s) DAAJ02-73-C-0071
9. PERFORMING ORGANIZATION NAME AND ADDRESS Boeing Vertol Company P.O. Box 16858 Philadelphia, Pennsylvania 19142		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task 1F162203A11902
11. CONTROLLING OFFICE NAME AND ADDRESS Eustis Directorate U.S. Army Air Mobility Research and Development Laboratory Fort Eustis, Virginia 23604		12. REPORT DATE November 1974 13. NUMBER OF PAGES 223
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Engine Reliability
Turbine Engines
Reliability

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The R&M problems of gas turbine engines were examined in a report entitled Investigation and Analysis of Reliability/Maintainability Problems Associated With Army Aircraft Engines. This study examines the Causal Factors which were identified as contributing to the R&M problems on current turbine engines and identifies and quantifies potential remedial actions which could improve future engine R&M characteristics.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (Continued)

The report is divided into three main sections. The first section discusses the approach and procedures used in the analysis; the second section presents the results of the analysis of Causal Factors, and the last section presents the results of the remedial action identification and summarization. Detailed work sheets for the identification, quantification, and summarization of remedial actions are included as Appendixes I and II.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure		Page
35	Remedial Action Subgroups for Decrease in Functional Requirements for Particular Baseline. .	82
36	Remedial Action Subgroups for a General Emphasis on R&M in Requirements for Composite Baseline. . .	89
37	Remedial Action Subgroups for a General Emphasis on R&M in Requirements for Particular Baseline . .	89
38	Remedial Action Subgroups for Additional Control of Engine/Airframe Interface for Composite Baseline	93
39	Remedial Action Subgroups for Additional Control of Engine/Airframe Interface for Particular Baseline	93
40	Remedial Action Subgroups for De-Emphasis on Acquisition Cost for Composite Baseline	97
41	Remedial Action Subgroups for De-Emphasis on Acquisition Cost for Particular Baseline	97
42	Remedial Action Subgroups for Closer Control of Operation of Engine for Composite Baseline	102
43	Remedial Action Subgroups for Closer Control of Operation of Engine for Particular Baseline. . . .	103
44	Time Phasing of Remedial Action Initiation	107

LIST OF TABLES

Table		Page

Table		Page

INTRODUCTION

The R&M problems of gas turbine engines were examined in report entitled "Investigation and Analysis of Reliability/ Maintainability Problems Associated With Army Aircraft Engines".[1] That analysis reviewed the historical experience of the following engines and installations.

TABLE I. ENGINES STUDIED

Engine	Manufacturer	Application	Service
T53-L-11 T53-L-13	Lycoming	UH-1 UH-1, AH-1	U.S. Army
T55-L-7 T55-L-7C	Lycoming	CH-47 CH-47	U.S. Army
T58-8B T58-10	General Electric	CH-46, SH-3 CH-46	U.S. Navy & Marines
T63-A5A	Allison	OH-6	U.S. Army
T64-6	General Electric	CH-53	U.S. Marines
T73	Pratt & Whitney	CH-54	U.S. Army
T74	United Acft of Canada	U-21 & Commercial	U.S. Army & Commercial

The R&M experience of these engines was examined at the common maturity point of approximately one million hours as an expression of the level of R&M of most general interest. All engines experience reliability growth during their operational phase (Figure 1), and an analysis at the one-million-hour point eliminates many of the developmental problems unique to specific configurations or uses and describes a more generic R&M condition.

---

1 Rummel, K. G., and Smith, H. J. M., INVESTIGATION AND ANALYSIS OF RELIABILITY AND MAINTAINABILITY PROBLEMS ASSOCIATED WITH ARMY AIRCRAFT ENGINES, Boeing Vertol Company, USAAMRDL Technical Report 73-28, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1973, AD772950

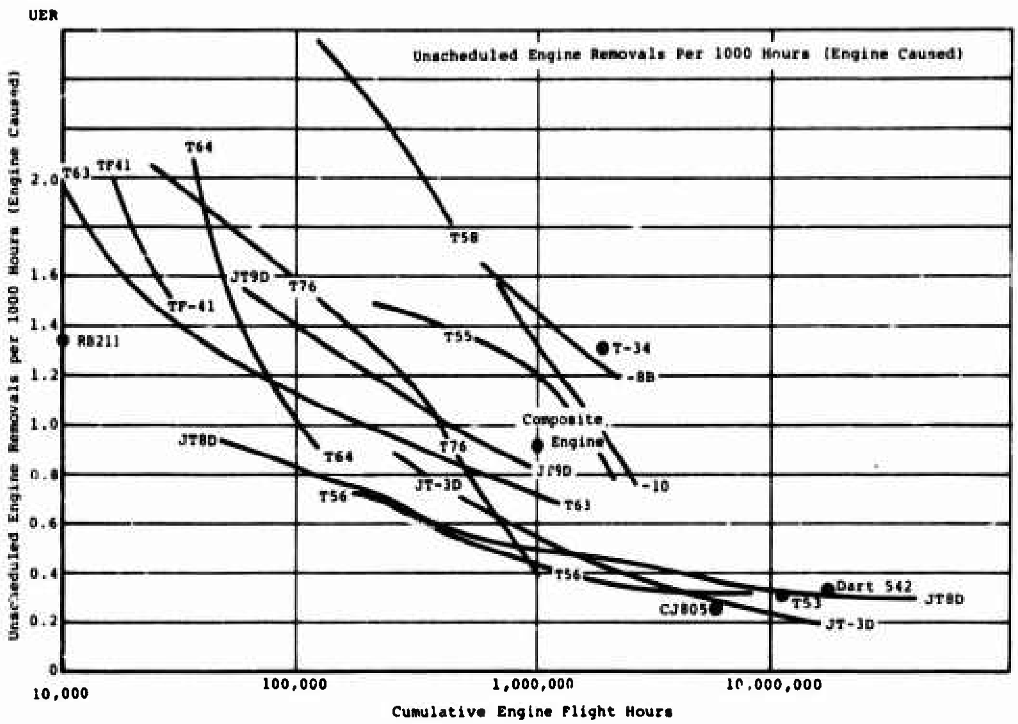

Figure 1. Engine Reliability Growth.

To describe the R&M problem, four basic measures or parameters were utilized:

- Unscheduled Engine Removal (UER) Rate (all causes)
- Major Accident Rate (engine-related)
- Maintenance Man-Hours/Flight Hour (MMH/FH) (on engine systems)
- Time Between Overhauls (TBO)

The experiences of specified engines were described in each of these parameters at the total engine, subsystem, and failure mode levels. For example, the engine subsystem distribution in the UER parameter is shown in Table II.

TABLE II. UNSCHEDULED ENGINE REMOVAL RATES

Subsystem	T53-L-11/11B UH-1 FY'67	T53-L-13/13A UH-1 FY'68	T55-L-7C 1971	T58-8B CH-46(SEA) 1/68-3/69	T58-8B SH-3 1/68-12/68	T58-10 CH-46(SEA) 1/69-2/70	T63-A-5A OH-6(SEA) 1/69-12/70	T64-6 CH-53(SEA) 1/68-12/69	T73 CH-54(SEA) 3/62-12/70	T74 Comm/ Military 6/70-5/71
Bearings	0.108	0.108	0.207	0.063	0.05[illegible]	0.046	0.170	0.230	0.081	0.005
Seals	0.074	0.340	0.243	0.838	0.073	0.138	0.158	0.097	0.081	-
Compressor	0.038	0.026	0.164	0.059	0.032	0.007	0.116	0.180	0.062	0.036
Combustion	0.008	0.001	0.190	0.117	0.038	0.007	0.002	0.033	-	-
Turbine	0.046	0.091	0.103	0.156	0.037	0.058	0.034	0.049	-	0.012
Cases	0.005	0.001	0.010	0.136	0.089	0.014	0.008	0.049	0.225	0.001
Lubrication	0.009	0.036	0.041	0.107	0.025	0.033	0.047	0.032	-	0.009
Fuel	0.003	0.004	0.071	0.380	0.166	0.163	0.030	0.032	-	0.003
Air	-	-	-	0.019	-	0.046	0.015	0.016	-	-
Accessory	0.008	0.003	0.063	0.049	0.032	0.019	0.016	0.048	-	0.010
Torquemeter	0.004	-	0.228	-	-	-	0.005	-	-	0.003
Electrical	-	-	-	0.039	0.013	0.065	-	0.016	-	0.009
Exhaust	-	-	0.006	-	-	-	0.007	-	0.021	0.009
Power-Train Reduction	0.006	0.036	-	-	-	-	-	-	-	0.010
Unknown*	0.018	0.051	0.151	0.241	0.032	0.052	0.[illegible]26	0.170	0.141	0.010
TOTAL - Engine Caused	0.328	0.703	1.479	2.212	0.598	0.650	0.834	0.959	0.604	0.117
Foreign-Object Damage	0.315	1.096	0.206	0.576	0.122	0.391	0.203	0.542		0.037
Erosion	0.450	0.053	0.076	0.478	-	0.065	0.009	0.132		-
Environmental	0.021	0.014	0.025	0.236	0.057	0.104	0.046	0.016		0.011
Operator Induced	0.143	0.110	0.145	0.203	0.039	0.104	0.190	0.098		0.008
Improper Maintenance	0.095	0.196	0.411	0.700	0.212	0.345	0.128	0.608		0.053
Convenience	0.358	0.392	1.667	0.360	0.038	0.645	0.335	0.657		-
Battle Damage/Crash	0.084	0.087	0.097	0.586	-	0.215	0.532	0.013		0.041
Airframe Related	0.036	0.121	0.121	0.400	0.045	0.423	0.002	0.180		0.005
Unknown*	0.090	0.162	0.308	0.448	0.025	0.194	0.530	0.487		0.013
TOTAL - Non-Engine-Caused	1.592	2.231	3.056	4.041	0.539	2.486	1.975	2.753	0.906	0.153
TOTAL - All Causes*	1.920	2.934	4.535	6.253	1.137	3.136	2.809	3.712	1.510	0.270

*Unknowns prorated proportionally to engine-caused and non-engine-caused UER's

The subsystem experience of the several engines examined was averaged for each of the four parameters to describe an average or composite engine as shown in Table III.

TABLE III. THE COMPOSITE ENGINE

	Subsystem	UER ($x10^{-3}$)	Accident Rate ($x10^{-6}$)	MMH Rate ($x10^{-3}$)	TBO* (800 Hr)
Engine Caused	Bearings	0.107	4.0	3.5	12%(0.02)
	Seals	0.205	0.4	4.7	
	Compressor	0.072	4.3	4.9	63%(0.13)
	Combustion	0.040	0	19.6	
	Turbine	0.058	2.3	19.9	25%(0.05)
	Cases	0.054	0.1	1.5	
	Lubrication	0.034	0.5	2.1	
	Fuel	0.085	4.8	9.8	
	Air	0.010	0	0.2	
	Accessories	0.025	0.7	2.3	
	Torquemeter	0.048	0.2	0.7	
	Electrical	0.014	0.1	3.9	
	Exhaust	0.004	0	0.7	
	Powertrain Reduction	0.013	0.3	0.4	
	SUBTOTAL	[illegible]69	17.[illegible]	74.2	100%(0.20)
Non-Engine-Caused	Foreign-Object Damage	[illegible]388	3.[illegible]	9.5	
	Erosion	0.140	1.7	2.4	
	Environmental	0.059	0	-	
	Operator Error	0.122	1.0	1.6	
	Improper Maintenance	0.305	1.7	7.6	
	Airframe Related	0.148	0.3	2.4	
	Convenience	0.495	0	9.5	
	Unknown	0.356	14.3	8.5	
	TOTAL	2.782	39.8	115.7	

*TBO interval of 800 hours is converted into removal rates and allocated to subsystems in Appendix I.

The experiences of the composite engine in each of the four parameters were combined into a single expression of R&M called the Index Number. This combining process was based on the cost impact of each of the four R&M parameters and produced Index Numbers at the engine subsystem level as shown in Table IV.

TABLE IV. COMPOSITE ENGINE SUBSYSTEM INDEX NUMBERS

	Subsystem	Index Number	Percent of Total
Engine Caused	Bearings	3.80	6.33
	Seals	3.46	5.76
	Compressor	4.63	7.71
	Combustion	1.14	1.90
	Turbine	2.86	4.76
	Cases	1.27	2.12
	Lubrication	1.28	2.13
	Fuel	3.45	5.75
	Air	0.55	0.92
	Accessories	0.91	1.50
	Torquemeter	1.27	2.12
	Electrical	0.73	4.22
	Exhaust	0.55	0.92
	Power-Train Reduction	0.72	1.20
	SUBTOTAL	26.62	44.34
Non-Engine-Caused	Foreign-Object Damage	6.71	11.19
	Erosion	2.90	4.83
	Environmental	1.09	1.82
	Operator Error	2.54	4.23
	Improper Maintenance	5.09	8.47
	Airframe Related	2.36	3.93
	Convenience	5.46	9.09
	Unknown		12.10
	TOTAL	60.03	100.00

The composite engine was also described at the failure mode level and is shown in Table V with both Index Numbers and the UER failures. (The UER is also shown since it is the most common and meaningful engine R&M parameter.)

TABLE V. COMPOSITE ENGINE SUMMARY MATRIX

	Index Number			Unscheduled Removals		
Subsystem/Failure Mode	Value	Subsystem Percent	All Causes Percent	Rate	Subsystem Percent	All Causes Percent
Bearings	3.80		6.33	0.107		3.85
Spalling - Classical (B-10)	0.42	11	0.70	0.006	6	0.22
Spalling - Nonclassical	1.86	49	3.10	0.033	31	1.18
Race Rotation/Displacement	0.61	16	1.02	0.032	30	1.15
Cage Wear/Cracking	0.50	13	0.83	0.018	17	0.65
Roller Skidding	0.30	8	0.50	0.013	12	0.47
Miscellaneous	0.11	3	0.18	0.005	5	0.18
Seals	3.46		5.76	0.205		7.37
Carbon-Seal Leakage	3.28	95	5.46	0.189	93	6.84
Labyrinth Seals	0.07	2	0.12	0.004	2	0.14
Static Seals and O-Rings	0.08	2	0.13	0.009	4	0.32
Miscellaneous	0.03	1	0.05	0.002	1	0.07
Compressor	4.63		7.71	0.072		2.59
Vane Failures - Erosion/Corrosion	1.11	24	1.85	0.028	38	1.00
Blade/Disc Fatigue Failure	2.40	52	4.00	0.006	8	0.22
Diffuser Cracking	0.28	6	0.47	0.022	30	0.79
Compressor Lining Wear	0.04	1	0.07	0.004	6	0.14
Variable Stator and Bleed	0.09	2	0.15	0.006	9	0.22
Miscellaneous	0.70	15	1.17	0.006	9	0.22
Combustion	1.14		1.90	0.040		1.44
Liner Cracking/Warping	0.19	17	0.32	0.007	17	0.25
Support Structure Cracking	0.19	17	0.32	0.007	17	0.25
Housing and Fitting Corrosion, etc.	0.58	50	0.96	0.020	50	0.72
Swirl Cup Wear/Cracking	0.17	15	0.28	0.006	15	0.22
Miscellaneous	0.01	1	0.02	-	1	
Turbine	2.86		4.76	0.058		2.08
Nozzle and Band Cracking	0.57	20	0.96	0.016	27	0.58
Nozzle Sulfidation/Burning	0.17	6	0.28	0.005	8	0.18
Support Structure and Fittings	0.54	19	0.90	0.025	44	
Blade and Wheel Cracks	1.17	41	1.96	0.001	1	0.04
Shaft and Couplings	0.23	8	0.38	0.003	6	0.11
Miscellaneous	0.17	6	0.28	0.008	14	0.29
Cases	1.27		2.12	0.054		1.94
Corrosion	0.27	21	0.45	0.012	23	0.43
Secondary Structural Cracks	0.45	35	0.75	0.017	31	[illegible]
Bosses Fittings, etc.	0.47	37	0.79	0.021	39	[illegible]
Miscellaneous	0.08	7	0.13	0.004	7	0.14
Lubrication	1.28		2.13	0.034		1.22
Pump Failures	0.60	47	1.00	0.017	49	0.61
Filters, Coolers, etc.	0.26	20	0.43	0.004	13	0.14
Tubes and Fittings	0.22	17	0.37	0.007	21	0.25
System Problems and Miscellaneous Hardware	0.20	16	0.33	0.006	17	0.22
Fuel	3.45		5.75	0.085		3.06
Fuel Control Units	2.58	75	4.30	0.058	68	2.08
Pumps, Valves, etc.	0.52	15	0.87	0.020	24	0.72
Tube, Lines and Fittings	0.18	5	0.30	0.002	2	0.08
Miscellaneous	0.17	5	0.28	0.005	6	0.18
Air	0.55		0.92	0.010		0.36
Control Valve Binding, Leak	0.38	70	0.64	0.007	70	0.25
Tubes, Fittings, and Miscellaneous Hardware	0.17	30	0.28	0.003	30	0.11
Accessory	0.91		1.50	0.025		0.90
Torquemeter	1.27		2.12	0.048		1.72
High-Speed Systems	1.21	95	2.02	0.046		1.65
Low-Speed Systems	0.06	5	0.10	0.002		0.07
Electrical	0.73		1.22	0.014		0.50
Ignition System Components	0.26	35	0.43	0.005	35	0.18
Power Management Systems	0.16	22	0.27	0.003	22	0.10
Wiring and Thermocouples	0.31	43	0.52	0.006	43	0.22
Exhaust	0.55		0.92	0.004		0.14
Power-Train Reduction	0.72		1.20	0.013		0.47
Inlet Air Separation	-		-	-		-
IR Suppression	-		-	-		-
TOTAL - Engine-Caused	26.62		44.34	0.769		27.64
Foreign Object Damage	6.71		11.19	0.388		13.95
Erosion	2.90		4.83	0.140		5.03
Environmental	1.09		1.82	0.059		2.12
Operator Induced	2.54		4.23	0.122		4.39
Improper Maintenance	5.09		8.47	0.305		10.96
Airframe Related	2.36		3.93	0.148		5.32
Convenience	5.46		9.09	0.495		17.79
TOTAL - Non-Engine-Caused	26.15		43.56	1.657		59.56
Unknown	7.26		12.10	0.356		12.6[illegible]
TOTAL - All Causes	60.03		100.0	2.782		

Each of these failure modes was examined in the basic report[1] and design information presented which related to these modes. This information consisted of:

- Discussion of the consequences of each failure mode.
- Variations in R&M experience across the various engines examined.
- Alternate design approaches to resolve these problems.
- Influences of aircraft, engine, or component operating conditions on R&M problems.
- Quantification of the current and potential R&M improvements available for future engines.

In addition to this basic design-oriented information, a more program-related analysis was performed. This analysis was directed at identifying the source of the R&M problems in terms of five causal or contributing factors. The five factors are shown in Figure 2.

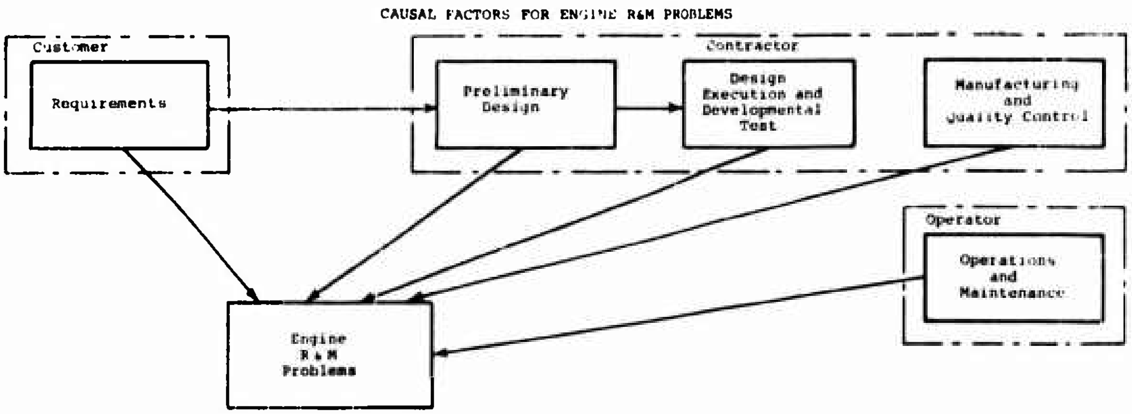

Figure 2. Interrelation of Causal Factors.

Problems on each engine in each failure mode were examined to determine the contribution of these Causal Factors. An example of this individual problem analysis is shown in Figure 3.

ENGINE T-XX
PROBLEM COMPRESSOR #1
UER RATE .036 CONTRIBUTING FACTORS ANALYSIS

	TOTAL CONTRI-BUTION PCT
DESCRIPTION OF PROBLEM: Diffuser scroll inserts loosening - air tubes to combustion chamber connect diffuser scroll with a concept using piston rings riding on sleeves which are threaded into magnesium scrolls. Deflection of scroll "legs" misalign tubes to scroll axis and piston rings gouge sleeve and cause axial movement and/or rotation of sleeve. This results in leakage of compressor discharge air out past sleeves.	
REQUIREMENTS: Customer indicated desire for highly modularized engine. Customer also desired low cost engine. Aggressive R&M goals were not present.	10
PRELIMINARY DESIGN: Concept that resulted from desire to modularize was one which split compressor air around gearbox and required use of tube connection. Cost considerations resulted in inexpensive piston ring design as opposed to more expensive bellows seal or other alternate concepts.	20
DESIGN EXECUTION AND DEVELOPMENT TEST: Did not consider deflection of scroll/tubes under air loads. Piston ring edges were not radiused adequately and surface finish of sleeve was not adequate.	70
MANUFACTURING OR QUALITY CONTROL:	
OPERATIONS OR MAINTENANCE:	

Figure 3. Example of Contributing Factors Analysis.

The results of these analyses are shown at the failure mode level in Table VI, at the subsystem level in Table VII, and at the total engine level in Figure 4.

TABLE VI. CONTRIBUTING FACTORS FAILURE MODE MATRIX							
			Contributing Factors - Percent				
Subsystem/ Failure Mode	Index Number	Percent	Requirements	Preliminary Design	Design Execution and Testing	Manufacturing and Quality Control	Operations or Maintenance
Bearings	3.80	-	12	9	67	7	5
Spalling - Classical (B_{10})	0.42	11	48	-	48	-	4
Spalling - Nonclassical	1.86	49	8	15	58	8	11
Face Rotation Displacement	0.61	16	12	8	70	10	-
Cage Wear/Cracking	0.50	13	10	-	78	7	5
Roller Skidding	0.30	8	-	12	88	-	-
Miscellaneous	0.11	3	-	-	-	-	-
Seals	3.46	-	20	22	50	5	3
Carbon Seal Leakage	3.28	95	20	22	50	5	3
Labyrinth Seals	0.07	2	40	50	10	-	-
Static Seals - O-Rings	0.08	2	10	20	50	10	10
Miscellaneous	0.03	1	-	-	-	-	-
Compressor	4.63	-	34	6	44	9	7
Vane Erosion - Failures	1.11	24	45	-	35	-	20
Blade/Disc Fatigue	2.40	52	31	8	47	14	-
Diffuser Cracking	0.28	6	34	5	52	-	9
Compressor Lining Wear	0.04	1	10	20	50	20	-
Variable Stator and Bleed	0.09	2	-	20	60	-	20
Miscellaneous	0.70	15	-	-	-	-	-
Combustion	1.14	—	28	7	55	7	3
Liner Cracking, Warping	0.17	17	-	-	100	-	-
Support Structure Cracking	0.19	17	20	20	60	-	-
Housing Corrosion and Fittings	0.58	50	43	7	38	5	7
Swirl Cup Problems	0.17	15	20	-	60	20	-
Miscellaneous	0.01	1	-	-	-	-	-
Turbine	2.86	—	46	3	42	3	6
Nozzle and Band Cracking	0.57	20	58	6	36	-	-
Nozzle Burning/Sulfidation	0.17	6	73	-	19	-	8
Support Structure and Fittings	0.54	19	13	6	53	16	12
Blades and Wheels	1.17	41	60	-	40	-	-
Shafts, Couplings	0.23	8	-	-	56		44
Miscellaneous	0.17	6	-	-	-	-	-
Cases	1.27	-	23	2	56		19
Corrosion	0.27	21	10	-	71	-	19
Secondary Structural Cracking	0.45	35	29	-	50	-	21
Bosses, Fittings, etc.	0.47	37	25	4	53	-	18
Miscellaneous	0.08	7	-	-	-	-	-
Lubrication	1.28	-	4	28	44	5	19
Pump Failures	0.60	47	-	45	45	-	10
Filters, Coolers, etc.	0.26	20	10	10	50	-	30
Tubes, Fittings, etc.	0.22	17	10	20	40	-	30
System and Miscellaneous Hardware	0.20	16	-	10	40	30	20
Fuel	3.45	—	24	22	28	1	25
Fuel Control Units	2.58	75	30	20	30	-	20
Pumps, Valves, etc.	0.52	15	2	40	10	5	43
Tubes, Fittings, etc.	0.18	5	-	-	50	-	50
Miscellaneous	0.17	5	-	-	-	-	-
Air	0.55	—	10		65	10	15
Valve Binding, Leaking	0.38	70	10	-	80	10	-
Tubes, Fittings, Miscellaneous Hardware	0.17	30	-	-	50	-	50
Accessory	0.91	-	-		80	20	1
Torquemeter	1.27		20	19	42		19
High-Speed System	1.21	95	20	20	40	-	20
Low-Speed System	0.06	5	-	-	100	-	-
Electrical	0.73	—	19	-	29	—	52
Ignition System Components	0.26	35	20	-	50	—	20
Power Management System	0.16	22	40	-	30	—	30
Wiring and Thermocouples	0.31	43	-	-	10	—	90
Exhaust	0.55	—	44	21	33		2
Power-Train Reduction	0.72	—	40	10	30	10	10
TOTAL - Engine-Caused	26.62	—	25	12	47	5	11
Foreign-Object Damage	6.71	—	70	10	5	-	15
Erosion	2.90		70	15	5	-	10
Environmental	1.09	—	-	20	-	-	80
Operator Induced	2.54	—	10	10	15	-	65
Improper Maintenance	5.09	—	10	5	5	5	75
Airframe Related	2.36	—	5	10	45	-	40
Convenience	5.46	—	-	-	-	-	100
TOTAL - Non-Engine-Caused	26.15	—	29	8	8		54
Unknown	7.26	—	—	—	—	1	—
TOTAL - All Causes	60.03	—	27	10	28	3	32

TABLE VII. CONTRIBUTING FACTORS SUBSYSTEM SUMMARY MATRIX

		Contributing Factors									
Subsystem or Mode	Index	Requirements		Preliminary Design		Design Execution		Manufacturing and Quality Control		Operation and Maintenance	
		Percent	Value	Percent	Value	Percent	Value	Percent	Value	Percent	Value
Bearings	3.80	12	0.45	9	0.34	67	2.55	7	0.27	5	0.19
Seals	3.46	20	0.69	22	0.76	50	1.74	5	0.17	3	0.10
Compressor	4.63	34	1.57	6	0.28	44	2.04	9	0.42	7	0.32
Combustion	1.14	28	0.32	7	0.08	55	0.63	7	0.08	3	0.03
Turbine	2.86	46	1.31	3	0.09	42	1.20	3	0.09	6	0.17
Cases	1.27	23	0.29	2	0.03	56	0.71	-	-	19	0.24
Lubrication	1.28	4	0.05	28	0.36	44	0.57	5	0.06	19	0.24
Fuel	3.45	24	0.83	22	0.76	28	0.97	1	0.03	25	0.86
Air	0.55	10	0.06	-	-	65	0.35	10	0.06	15	0.08
Accessory	0.91	-	-	-	-	80	0.73	20	0.18	-	-
Torquemeter	1.27	20	0.25	19	0.24	42	0.54	-	-	19	0.24
Electrical	0.73	19	0.14	-	-	29	0.21	-	-	52	0.38
Exhaust	0.55	44	0.24	21	0.12	33	0.18	-	-	2	0.01
Power-Train Reduction	0.72	40	0.29	10	0.07	30	0.22	10	0.07	10	0.07
Total - Engine-Caused	26.62		6.49 24%		3.13 12%		12.64 48%		1.43 5%		2.93 11%
Foreign Object Damage	6.71	70	4.70	10	0.66	5	0.34	-	-	15	1.01
Erosion	2.90	70	2.02	15	0.44	5	0.15	-	-	10	0.29
Environmental	1.09	-	-	20	0.22	-	-	-	-	80	0.87
Improper Operation	2.54	10	0.25	10	0.25	15	0.38	-	-	65	1.66
Improper Maintenance	5.09	10	0.51	5	0.25	5	0.25	5	0.25	75	3.83
Airframe Induced	2.36	5	0.12	10	0.24	45	1.06	-	-	40	0.94
Convenience	5.46	-	-	-	-	-		-	-	100	5.46
Total - Non-Engine Caused	26.15		7.60 29%		2.06 8%		2.18 8%		0.25 1%		14.06 54%
Unknown	7.26										
Total - Engine	60.03		14.09 27%		5.19 10%		14.82 28%		1.68 3%		16.99 32%

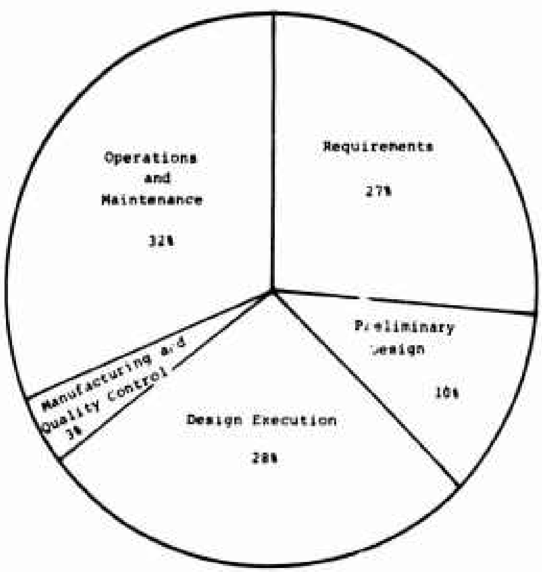

Figure 4. Summary Results of Contributing Factors.

This analysis provided a general indication of the source of problems within the development and procurement cycle of an engine. It did not, however, provide specific guidance for remedial actions. This report documents a study which further analyzes these causal factors and identifies those specific remedial actions that could be implemented by both customer and contractor to address the various R&M problems.

STUDY APPROACH AND PROCEDURES

The basic objectives of this study were to examine the Causal Factors which were identified in Reference 1 as contributing to the R&M problems on current turbine engines and to identify and quantify potential remedial actions which could improve future engine R&M characteristics.

This report is divided into three main sections. This section discusses the approach and procedures used in the analysis. The following section presents the results of the analysis of Causal Factors, and the last section presents the results of the remedial action identification and summarization. Appendixes I and II are the detailed work sheets for the identification, quantification, and summarization of remedial actions.

Throughout the analysis, two basis measures of R&M are used: the Index Number and the unscheduled removal from the airframe rate. The Index Number was introduced in Reference 1 and is a constructed value integrating the weighted effects on unscheduled removals, accidents, TBO intervals and maintenance man-hours of each failure mode. The unscheduled removal rate is also included in this analysis because of its familiarity and more general usage by the engine communities. The historical experience in both of these parameters for each failure mode is provided in Reference 1.

The analysis begins with a thorough examination of the five Causal Factors identified as contributing to the current experience on Army and Navy turboshaft and turboprop engines. Each Causal Factor contributes to a variety of failure modes. Some failure modes had all five Causal Factors contributing to their source; most had two or three prime contributing factors. Each failure mode that appeared in the five Causal Factors was reexamined to determine more specifically the nature of the Causal Factor influences.

As a result of this examination, lower levels of Causal Factors were identified and termed Factor Elements. As an example of this process, the Specifications and Requirements Causal Factor has the following Factor Elements identified.

- Lack of Requirements for Specific Features
- Performance/Weight Emphasis
- Acquisition Cost Emphasis
- Requirements for Specific Features

- Program Schedule Emphasis

- General Lack of R&M Emphasis

The identification of these Factor Elements clearly suggests different types of remedial action and can provide, therefore, a clear identification of specific customer action that would be required for resolution of that R&M problem.

With these Factor Elements established, remedial actions could be identified. Each failure mode in each Factor Element was examined for one or more remedial actions. Figure 5 illustrates how this was performed and documented. Concurrent with this identification of remedial actions, their benefits were quantified as also illustrated in Figure 5. The quantification was performed in two dimensions. First, the benefits were calculated against two engine baselines. The first baseline, called the Composite, is the average R&M experience of current engines and is described in the introductory section of this report. The second baseline is called the Particular and is the R&M experience of a particular engine design or failure mode against which the remedial action could have very high or very low benefits.

The concept of the Particular engine was introduced when it became clear that the full potential of any remedial action cannot be quantified if the historical experience reflects a partial or complete incorporation of this remedial action. In other words, the Composite engine, since it represents a variety of engine configurations and design approaches, minimizes the R&M impact of any single problem and therefore the benefit of solving that problem. In terms of usage, both baselines have value. The benefits against the Composite engine provide a prioritization of remedial actions for long-term consideration by the engine community. The benefits of the Particular baseline, on the other hand, provide a prioritization of remedial actions that indicate the importance of program and design decisions on a specific engine program under consideration. To illustrate this point, the decision between an all-axial-flow compressor and an axial/centrifugal compressor is concerned only with effects on that specific engine and not what effect that decision would have if made on all engines in the entire inventory of existing military engines. Conversely, the priority given to improved technology should be viewed in the context of its potential return on the entire inventory of military engines and not on what it would

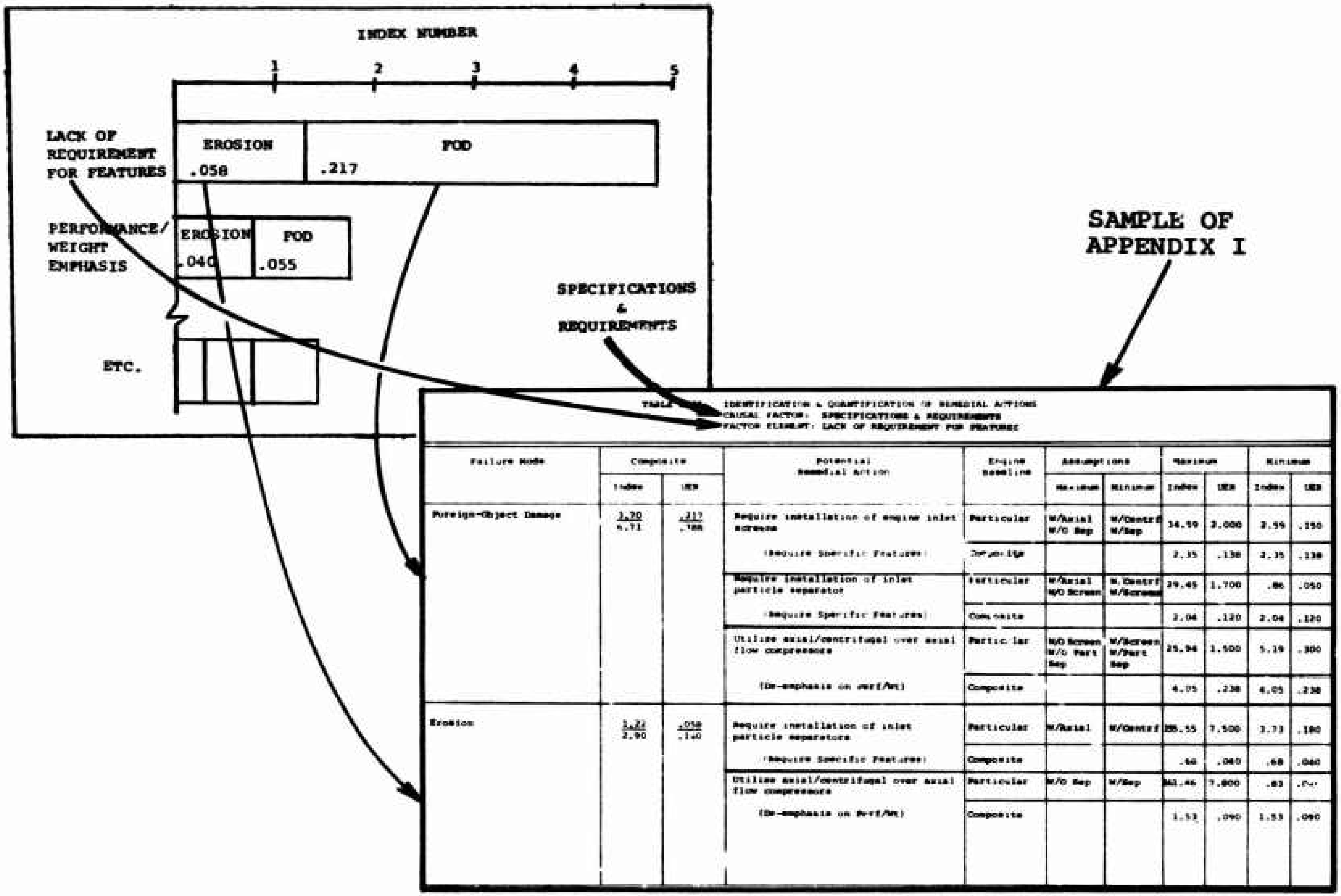

Figure 5. Remedial Action Identification and Quantification Flow Process.

contribute to a single engine program of a specific configuration and technology base.

The second dimension to the quantification process was a maximum and minimum calculation of benefit. This variation is utilized in conjunction with the two baselines to indicate the full range of benefits that any remedial action could provide. This matrix of maximum and minimum against the Particular and Composite baselines is shown in Figure 5, which also indicates that the assumptions inherent in each calculation are identified.

Having examined each failure mode for potential remedial action and quantified their potential benefits, all similar remedial actions were summarized regardless of the failure modes affected. This summarization process is illustrated in Figure 6. All remedial actions were assigned to fifteen major groups. Within many of the major groups, common remedial actions formed subgroups which will provide a better understanding of the requirements for initiation and implementation, technology status and cost effectiveness.

These remedial action groups were then prioritized by their benefit against both Particular and Composite baselines.

In establishing remedial actions and their groups, major emphasis was placed on providing visibility of the value of alternate approaches to improved R&M by the customer. Because of this emphasis, alternate remedial actions were applied against the same failure mode. This reflects the real world where many problems can be and have been resolved through a variety of corrective actions. Because of this approach, the sum of all remedial actions is greater than the initial problem. Readers utilizing this study to quantify potential benefits, given the implementation of several remedial actions, must be careful that a given problem is not counted as being resolved more than once. This approach does, however, allow an overall perspective of which remedial actions would be beneficial and also provides the detailed quantification that could support R&M predictions on any given program in response to specific remedial actions that are considered for incorporation.

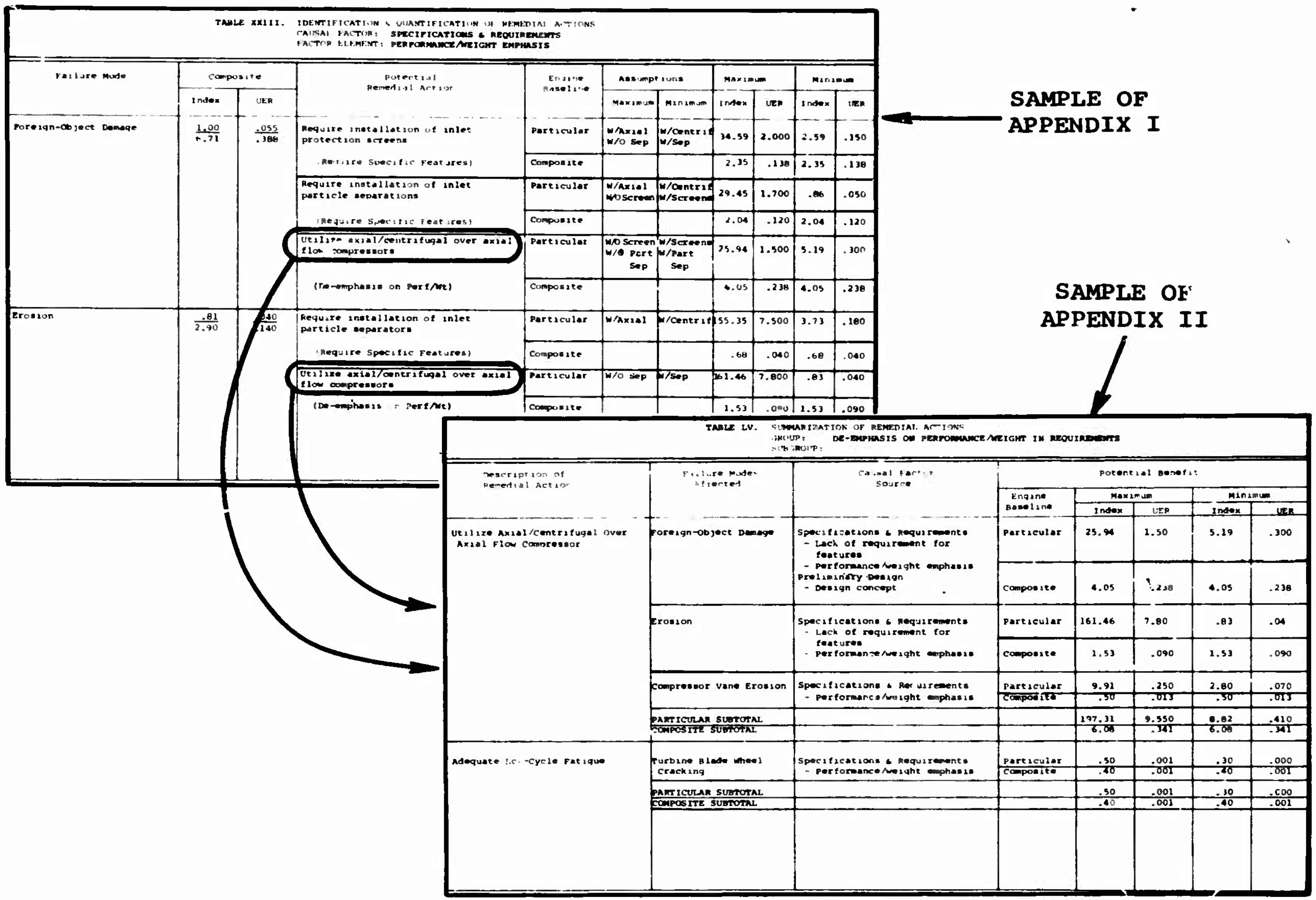

TABLE XXIII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: PERFORMANCE/WEIGHT EMPHASIS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Foreign-Object Damage	1.00 / 4.71	.055 / .388	Require installation of inlet protection screens	Particular	W/Axial W/O Sep	W/Centrif W/Sep	34.59	2.000	2.59	.150
			(Require Specific Features)	Composite			2.35	.138	2.35	.138
			Require installation of inlet particle separations	Particular	W/Axial W/O Screen	W/Centrif W/Screens	29.45	1.700	.86	.050
			(Require Specific Features)	Composite			2.04	.120	2.04	.120
			Utilize axial/centrifugal over axial flow compressors	Particular	W/O Screen W/@ Part Sep	W/Screens W/Part Sep	25.94	1.500	5.19	.300
			(De-emphasis on Perf/Wt)	Composite			4.05	.238	4.05	.238
Erosion	.81 / 2.90	.040 / .140	Require installation of inlet particle separators	Particular	W/Axial	W/Centrif	55.35	7.500	3.73	.180
			(Require Specific Features)	Composite			.68	.040	.68	.040
			Utilize axial/centrifugal over axial flow compressors	Particular	W/O Sep	W/Sep	161.46	7.800	.83	.040
			(De-emphasis on Perf/Wt)	Composite			1.53	.090	1.53	.090

TABLE LV. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: DE-EMPHASIS ON PERFORMANCE/WEIGHT IN REQUIREMENTS
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Utilize Axial/Centrifugal Over Axial Flow Compressor	Foreign-Object Damage	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis Preliminary Design - Design concept	Particular	25.94	1.50	5.19	.300
			Composite	4.05	.238	4.05	.238
	Erosion	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis	Particular	161.46	7.80	.83	.04
			Composite	1.53	.090	1.53	.090
	Compressor Vane Erosion	Specifications & Requirements - Performance/weight emphasis	Particular	9.91	.250	2.80	.070
			Composite	.50	.013	.50	.013
	PARTICULAR SUBTOTAL			197.31	9.550	8.82	.410
	COMPOSITE SUBTOTAL			6.08	.341	6.08	.341
Adequate Lo-Cycle Fatigue	Turbine Blade Wheel Cracking	Specifications & Requirements - Performance/weight emphasis	Particular	.50	.001	.30	.000
			Composite	.40	.001	.40	.001
	PARTICULAR SUBTOTAL			.50	.001	.30	.C00
	COMPOSITE SUBTOTAL			.40	.001	.40	.001

Figure 6. Summarization of Remedial Action Flow Process.

RESULTS OF CAUSAL FACTOR ANALYSIS

The concept of Factor Elements was introduced in the preceding section. Factor Elements were used to further understand the Causal Factors in the sense that further remedial actions could be identified once the origins of each R&M problem were clearly identified. The five main Causal Factors which required this Factor Element analysis are:

- Specifications and Requirements
- Preliminary Design
- Design Execution and Testing
- Manufacturing and Quality Control
- Operations and Maintenance

SPECIFICATIONS AND REQUIREMENTS

This factor reflects those problems that originate during the earliest stages of establishing the overall engine requirements and extend into the time when the major design alternates or features are being generated in response to the basic requirements. In other words, it reflects problems that arise from the designs or features that are in immediate response to a specified requirement. The contribution of Specifications and Requirements to the total engine problem is shown in Figure 7.

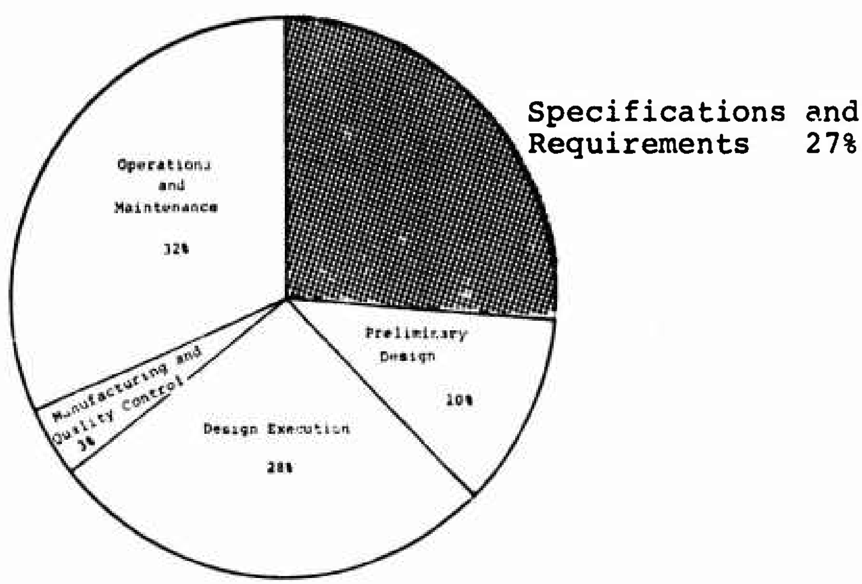

Figure 7. Contribution of Specifications and Requirements.

The Factor Elements that were defined in order to understand the Causal Factors of Specifications and Requirements are as follows:

- <u>Lack of Requirements for Specific Features</u>

  This element reflects the impact of not requiring those features which will be installed only if specifically required in the basic specifications. Although they have a performance, weight, or acquisition cost impact, they would be incorporated regardless of these penalties if so required. Conversely, if not required, it is highly unlikely that they would be incorporated.

  In actuality, this element addresses only the modes of FOD and erosion and illustrates the impact of not requiring the features for inlet protection screens and/or particle separators, filters, etc.

- <u>Performance/Weight Emphasis</u>

  The problems assigned to this element arose when an emphasis on high performance (low weight) dictated the selection of design approaches which compromised R&M. While the selection of these R&M degrading designs was not specified, the usual competitive pressures, coupled with the lack of emphasis and measurability of R&M as opposed to performance and/or weight, made the selections virtually inevitable.

- <u>Acquisition Cost Emphasis</u>

  This element includes the problems that arose when a desire for a low acquisition cost dominated an R&M objective (whether a R&M requirement was specified or not).

- <u>Requirements for Specific Features</u>

  Certain problems arise due to requirements for specific design features. There are features over and above, so to speak, the basic function of the engine and are usually designed either to ease pilot work-load or to incorporate into the engine features that could be considered part of the airframe design, i.e.,

torquemeters.

- Program Schedule Emphasis

  Those problems which originated due to the pressures of time/schedules are included in this element. It reflects basically the inability to design and manufacture an alternate design as opposed to the lack of time for general developmental testing that would have precluded many or most of the R&M problems examined in this report.

- General Lack of R&M Emphasis

  Problems grouped in this factor element include those which originated when an emphasis on R&M was not present. Since this resolution did not usually have a significant weight, cost or schedule penalty, failure to eliminate or minimize these problems cannot be attributed to an emphasis on these characteristics, but rather due to a general lack of R&M emphasis.

These Factor Elements contribute to the Specifications and Requirements Causal Factor and are shown in Figure 8.

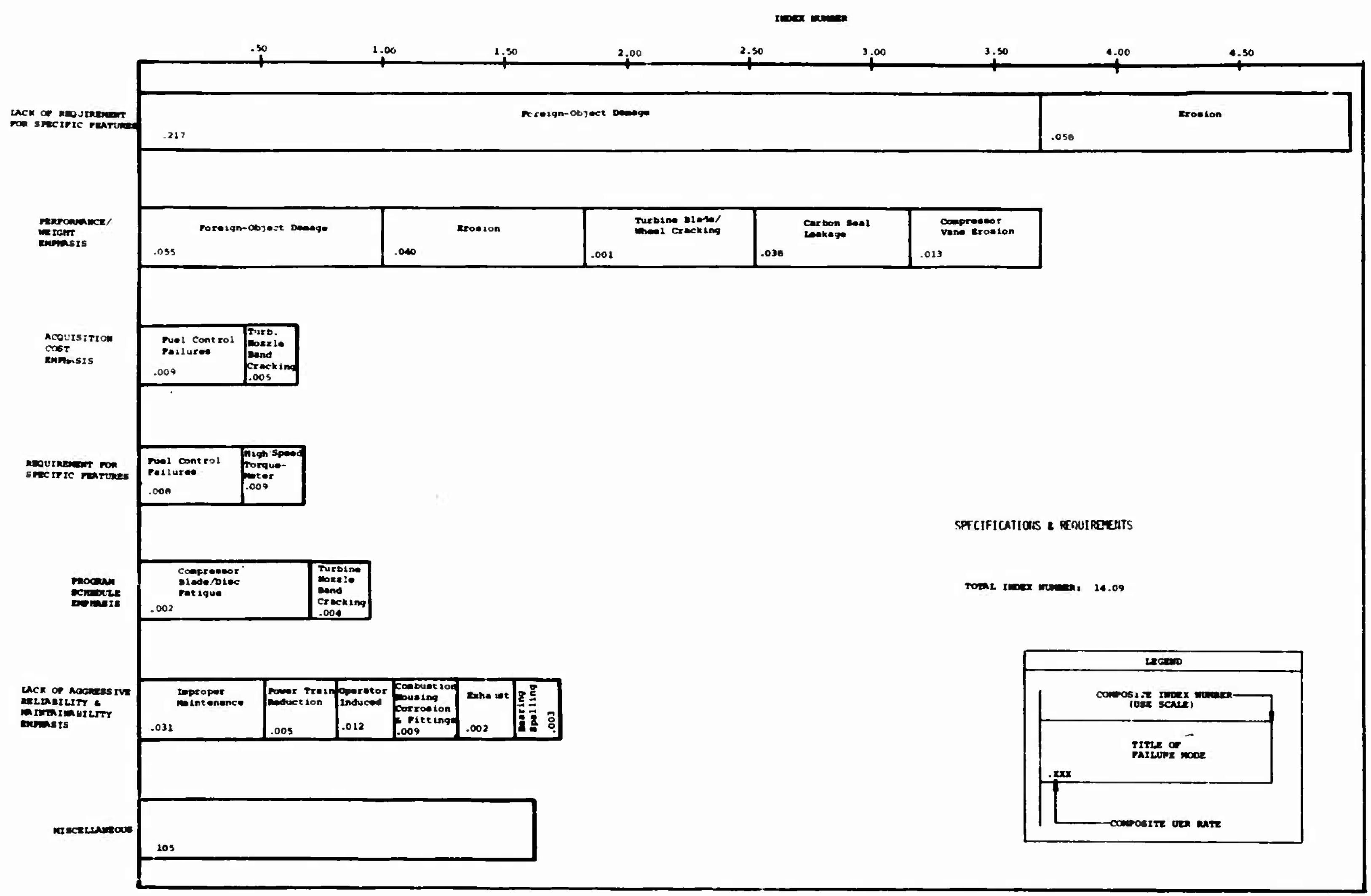

Figure 8. Factor Elements for the Specifications and Requirements Causal Factor.

Discussion of Results for Specifications and Requirements

The contribution of the Lack of Requirements for Specific Features is the largest single Factor Element and consists of portions of only two failure modes. It alone is nearly 40% of the total. The element for problems originated when a Performance and/or Weight Emphasis was prevalent is the next largest Factor Element with a 30% contribution.

These two elements plus the next three of Acquisition Cost Emphasis, Requirement for Specific Features, and Program Schedule Emphasis are the result of specific and direct customer specification of objectives. The last Factor Element - Lack of Aggressive R&M Emphasis - is a source of problems more general than the previous elements in that it reflects the contractor's response to the absence of a requirement. This Factor Element is viewed as a source of problems that will not be relieved by just the de-emphasis of the non-R&M objectives but will require specific and clearly understood aggressive R&M requirements.

The rather low contribution of Acquisition Cost Emphasis as a source of R&M problem in this analysis confirms the authors' impressions from past discussion with engine manufacturers, where generally they did not feel that the objective of lowest possible acquisition cost, currently gaining even more emphasis, was a significant restraint to achieving improved R&M. The reader is cautioned, however, that the Factor Element of Lack of Requirement for Specific Features has strong cost overtones. The cause for past reluctance to specify complete inlet protection systems may be as much a cost issue as a performance/weight issue. Thus, the previous conclusion that acquisition cost is not a strong factor in poor R&M must be somewhat tempered by this possibility.

The overall conclusion from the display is that the problems arising from Specifications and Requirements are highly driven by the influence of a few competing requirements, most of which are the direct result of customer specifications, and that the specific failure modes that are potentially affected are highly visible. Remedial action would seem to have the potential to be extremely powerful.

PRELIMINARY DESIGN

This Causal Factor is assigned to those problems which result from design approaches chosen during the early stages of the design evolution. This factor is different from the Specifications and Requirements factor in that the design approaches taken were not in direct response to top-level requirements initially specified. In other words, they were options that the engine manufacturer selected largely independent of the customer's early general or specific requirements. It is this early timing of the decisions and the obvious nature of the design choices that distinguish this Causal Factor from the factor of Design Execution. The contribution of Preliminary Design to the total engine problem is shown in Figure 9.

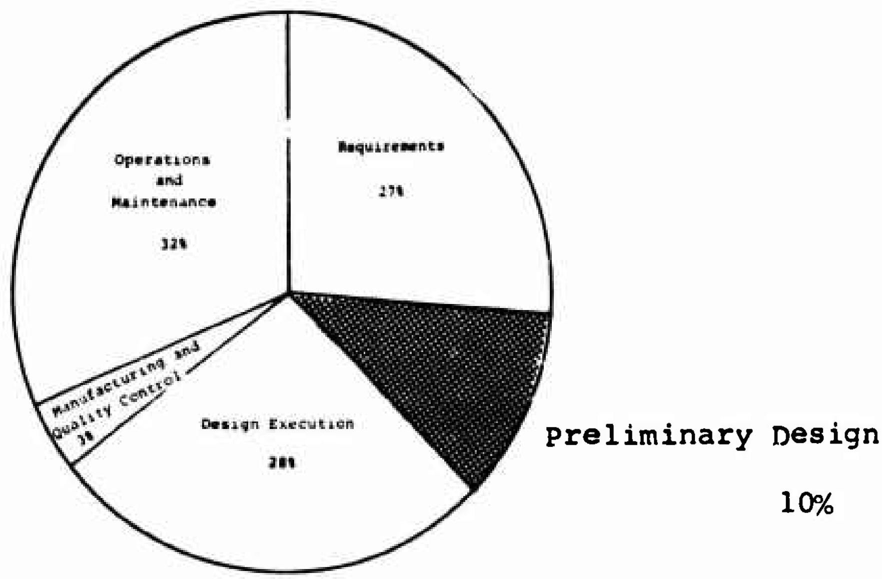

Figure 9. Contribution of Preliminary Design.

The Factor Elements that were defined in order to understand the Causal Factor of Preliminary Design are as follows:

- Engine/Airframe Physical Interface

  This element is largely self-explanatory and relates to problems arising when the installation of the engine into the airframe is poor or at least uncoordinated. In terms of assigned responsibility these problems are due to more inadequate airframe contractor engineering than engine contractor efforts.

* <u>Overall Engine Configuration</u>

  Problems clearly originating from the basic arrangement or configuration of the engine are included in this element. Arrangement in this element is the basic placement of the various engine modules with respect to each other, i.e., combustion in relation to turbine.

* <u>Design Concepts</u>

  This element includes problems or portions of problems that arose from the selection of design approaches of specific functional elements of the engine, i.e., seal type, fuel control operating media, etc.

* <u>Detailed Design Configuration</u>

  More detailed design considerations are viewed as the causes of problems in this element.

* <u>Internal Arrangement</u>

  Problems arising from the placement of individual components within the engines are classified in this element.

* <u>Material Selection</u>

  General uses of materials engine-wide that are not optimum from an R&M standpoint were the driving factors in problems assigned to this category.

* <u>Manufacturing Approach</u>

  The few problems that arose due to a particular manufacturing approach are considered under this Factor Element.

These Factor Elements contribute to the Preliminary Design Causal Factor as shown in Figure 10.

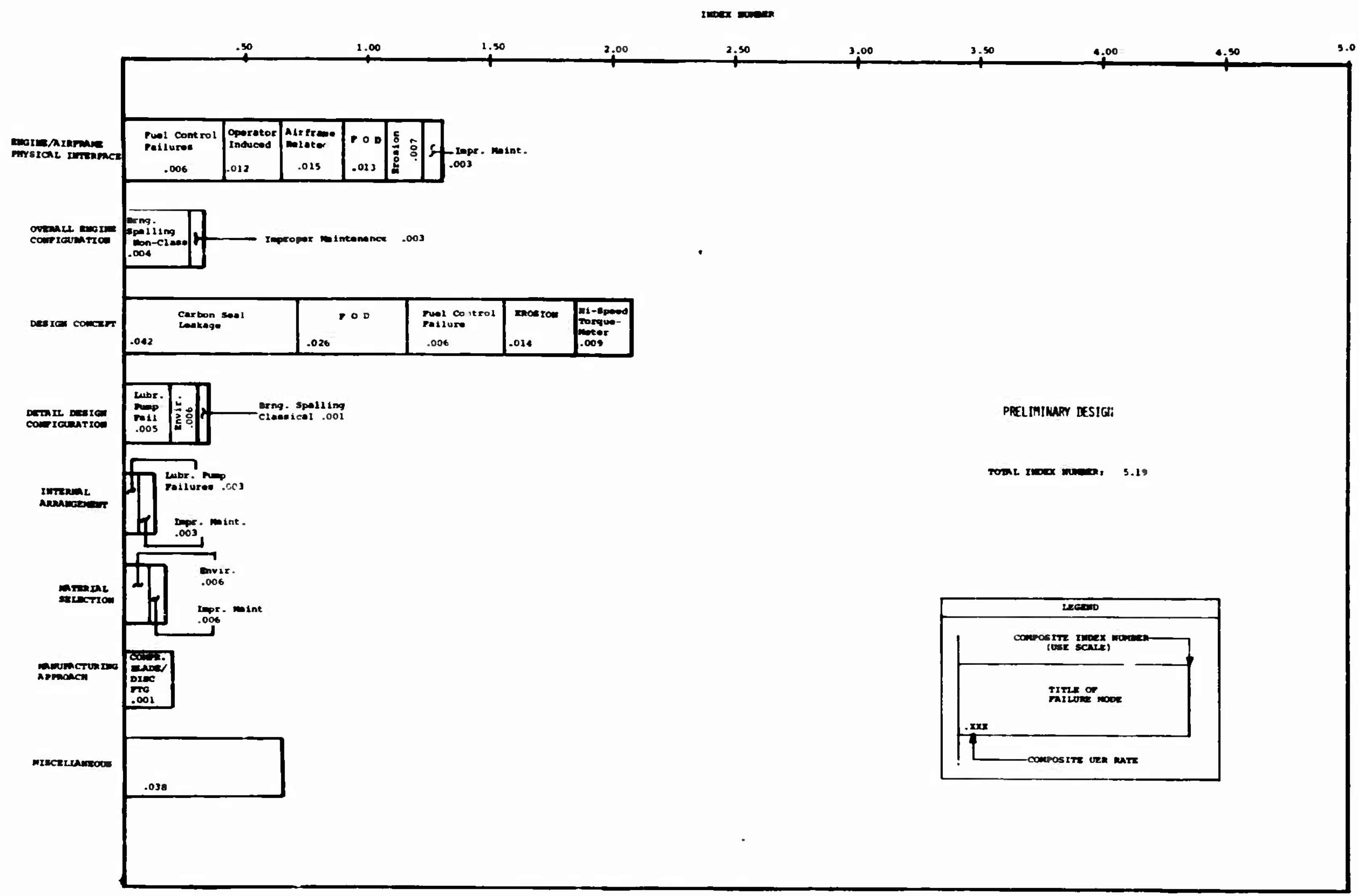

Figure 10. Factor Elements for the Preliminary Design Causal Factor.

Discussion of Results for Preliminary Design

The Factor Elements are arranged on Figure 10 in descending order of customer visibility. More obvious and controllable problem sources such as engine/airframe interface, overall engine configurations, and design concepts are placed at the top and contribute to over 80% of the total Preliminary Design.

The Engine/Airframe Interface element arises more from a consideration of the physical installation and engine control aspects than from a dynamic loads standpoint. Inability of the engine to withstand the "normal" airframe vibration - as opposed to the more complex drive train dynamics - is not assigned to the Causal Factor of Preliminary Design but Design Execution and Testing. It is extremely difficult to identify specific problems that have as their origin an inadequate interface between engine and airframe manufacturers in the area of drive train dynamics/loads. Whether this is due to the actual absence of these types of problems in relatively mature installations or the subtle nature and corresponding difficulty in identification is not clear. The authors lean toward the former position. The past policy of separate engine/airframe procurements contributes to these problems. Nevertheless, improvements are possible within this framework through improved engine/airframe interface agreements encouraged by the customer.

The element of Overall Engine Configuration did not appear as a large contributor to the past R&M problems despite the great variety of engine configurations examined. Only the modes of bearing spalling and maintenance damage were affected by unique configurations, leading to the conclusion that nearly all configurations can be made reliable.

The impact of Design Concepts is considerable. Failure modes contributing to this element are relative few and highly visible. As the largest single Factor Element within Preliminary Design, it offers an opportunity for significant improvement in the future by direct control by the procuring body.

This control can be manifested as a selection of an engine configuration/manufacturer during a competive evaluation process or it can be manifested more directly during the design stages immediately subsequent to the selection point. This later type of control, however, can only be accomplished when the contractual environment has been structured to allow direct

involvement of the customer in these traditionally intimate decisions.

Lower levels of more detailed Factor Elements contribute considerably less to the total R&M problem, reflect a few failure modes on a few specific engines, and do not, therefore, represent general trends.

The general conclusion that appears appropriate when examining the Preliminary Design Causal Factor is similar to the conclusions surrounding the Specifications and Requirements Causal Factor; that is, a relatively few failure modes arising from rather visible and therefore controllable design and/or program sources are the real contributors. Remedial action on these modes should have a significant impact.

DESIGN EXECUTION

Problems are assigned to this Causal Factor when they result from inadequacies occurring in the stages of engine development beyond the initial phases of sizing and configuration selection. The primary tasks of interest are the detail design of the hardware and the analytical activities surrounding this function, including the planning and performance of the complete development test program. Since most of the activity at this stage is of a rather detailed level, customer influence can only be of an indirect nature. This Causal Factor is the second largest, as shown in Figure 11.

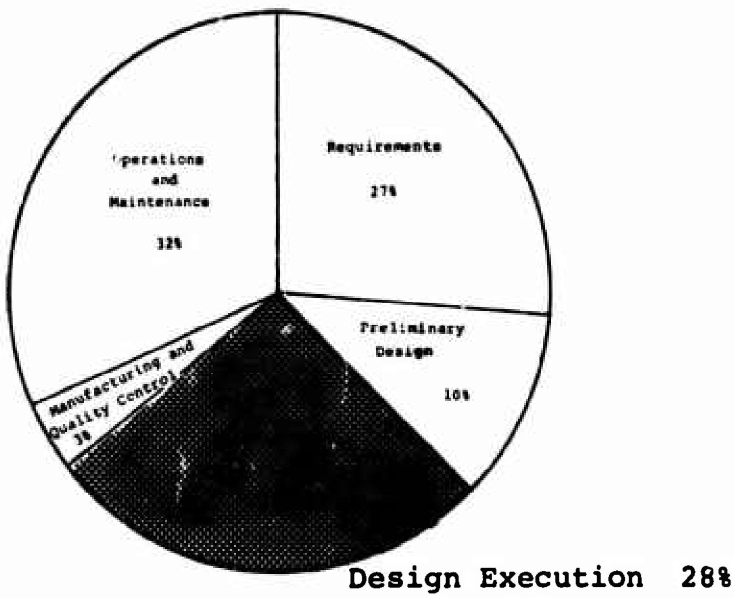

Figure 11. Contribution of Design Execution.

The Factor Elements that were defined in order to understand this factor were specifically designed to indicate the ability of the customer to improve R&M in this area, recognizing the indirect nature of such an influence. Accordingly, the following Factor Elements concentrate on displaying the ability or likelihood that customer initiated or controlled remedial actions could be beneficial in the future.

* **Analysis Available - Not Used - Reasonable Cost**

  This element reflects those problems whose solutions were design analyses which were available at the time of initial design and which were apparently not performed due to the competing pressures on available funds and time. The solutions (additional analysis) are viewed by the authors as possessing reasonable potential for preventing the problem (effectiveness) at a reasonable expenditure of time and effort (costs). As such, this Factor Element and the problems allocated to it would be prime candidates for improvement if additional funds and/or time were allocated to R&M improvement.

* **Analysis Available - Not Used - Not Cost Effective**

  Where the solution/prevention of problems involved analysis methods which were available but required excessive time/effort beyond their expected benefit, this Factor Element was used. In other words, this element is used to describe problems that are unlikely to be resolved by additional R&M emphasis since their solution simply involves more effort than it would be worth. In a sense, remedial actions which are too inefficient to be practically utilized are not remedial actions at all, and as such represent inadequate technology. However, it was felt that a need existed to categorize those problems which were halfway between those routinely correctable by analytical procedures and those problems not correctable by any known technical approach other than testing. As such, this element simply represents the midpoint of a continuum from "can be" to "cannot be" resolved.

* **Inadequate Technology**

  This Factor Element is reserved for those failure modes where analytical capabilities are clearly lacking. Many of the design problems that would ultimately be assigned to this category were (are) handled as an art rather than a science. This element would provide clear indication where improved analytical capability would be beneficial.

These Factor Elements contribute to the Design Execution Causal Factor as shown in Figure 12.

Discussion of Results for Design Execution

The Factor Elements are arranged in Figure 12 in descending order of their ability to respond to increased R&M emphasis.

The Analyses Available - Not Used - Reasonable Cost Effectiveness is the largest single element but is only 40% of the total. The portions of failure modes assigned to this element could respond to additional time and funds with a high degree of assurance that R&M benefits would accrue. From a more discouraging viewpoint, the next two categories of Analyses - Not Used - Not Cost Effective and Inadequate Technology comprise 60% of the Design Execution Causal Factor. An inspection of the failure modes in the Not Cost Effective Analyses element reveals a pattern of failure modes of either minor consequences or that result from complex load or temperature sources. The Inadequate Technology element reveals failure modes of more serious consequences but where testing has been the only effective means of problem control or design verification. The fact that so much research has been directed at these failure modes and they still remain largely an art suggests that only testing can be relied upon for effective control in the immediate future. The view that the Causal Factor of Design Execution has indirect response to the lack of aggressive R&M emphasis must be tempered by the acknowledgement of the limitations of our engineers, analytical techniques, materials capabilities, and the available funds and time in which to develop engines. The magnitude of the unaddressable problems clearly suggests that a variety of remedial actions are appropriate - ranging from increased research into the understanding of certain failure modes to the use of proven designs for new airframe applications. Increased R&M emphasis on a specific engine can only have limited benefits for problems in this Causal Factor.

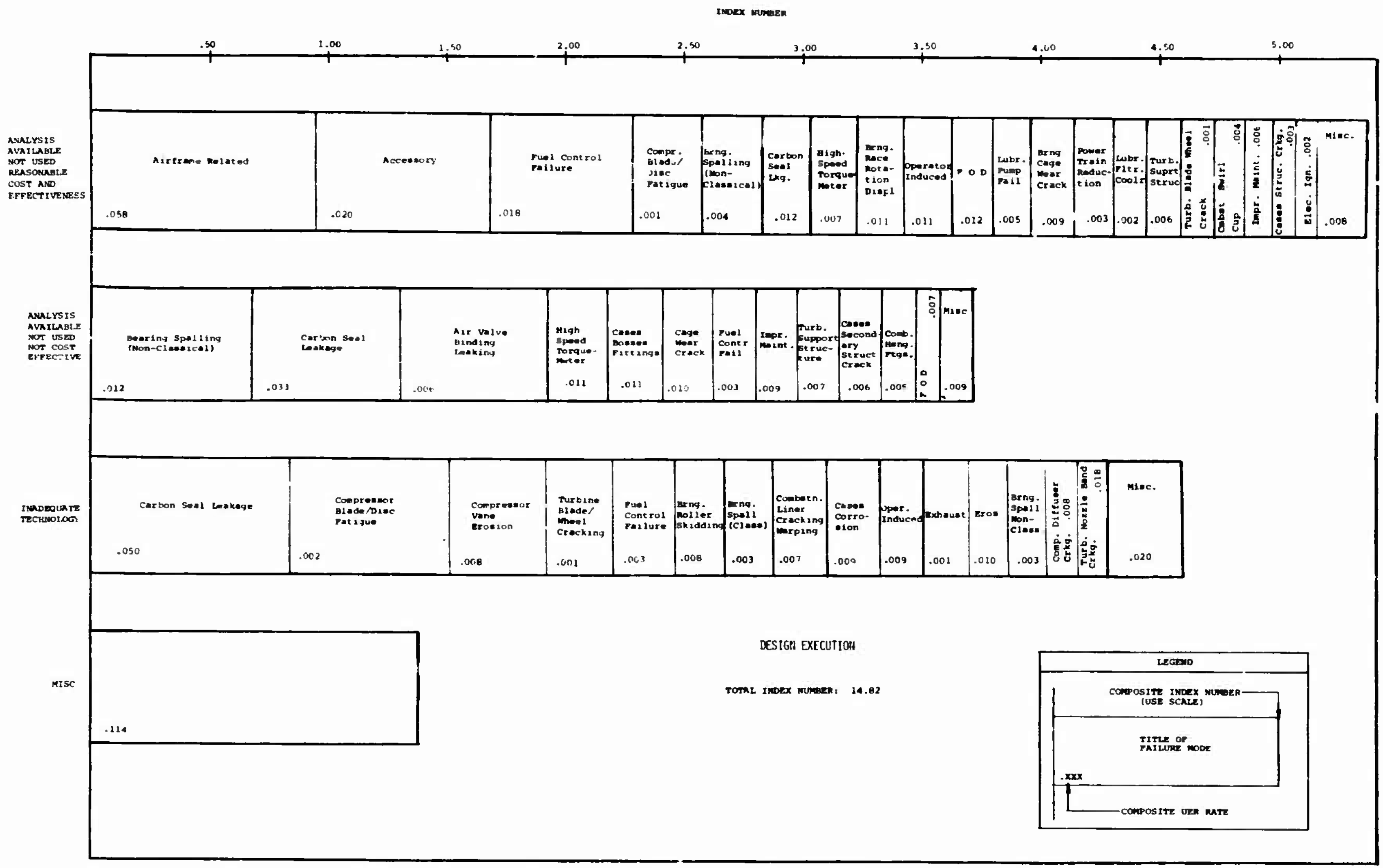

Figure 12. Factor Elements for the Design Execution Causal Factor.

MANUFACTURING AND QUALITY CONTROL

This Causal Factor is specifically those problems which appear due to inadequate manufacturing and/or inspection (quality control) of the engine. To be classified into this element, reasonable design provisions had to have been made for the manufacturing and inspection processes. This factor includes the overhaul/repairs performed by the military user at his depot facilities. This category excludes, therefore, the field or intermediate level maintenance-induced problems. The contribution of this Causal Factor to the total engine problem is shown in Figure 13.

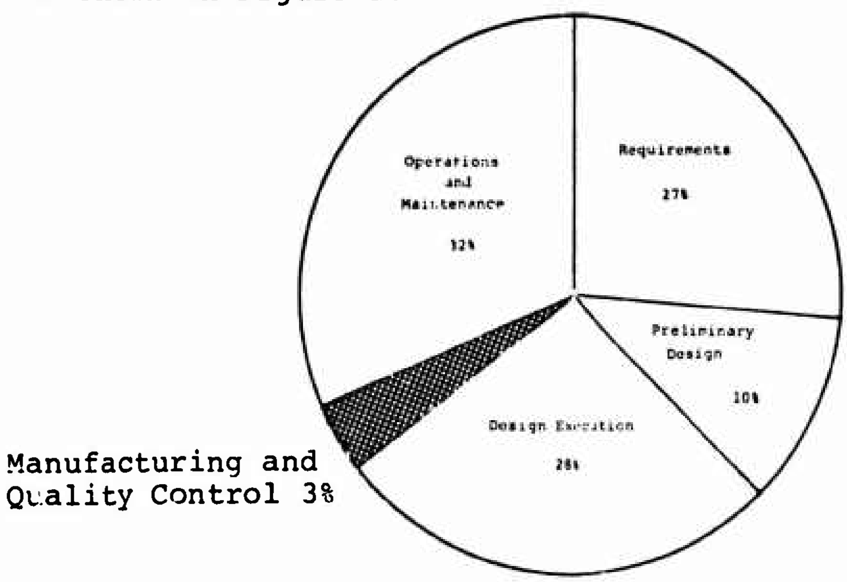

Figure 13. Contribution of Manufacturing and Quality Control.

The following Factor Elements were established for the Causal Factor of Manufacturing and Quality Control.

- <u>Optimum Assembly/Quality Control Procedures Not Utilized</u>

  This element is designed to represent those instances where a procedure which could have precluded the problem was available but not utilized. The implication is that these problems are not the result of errors or misjudgement of individual manufacturing or quality control personnel, but a lack of adequate procedures or criteria. This element describes those problems which could be reduced or eliminated if additional effort was applied.

* <u>Alternate Assembly/Quality Control Procedures Not Available</u>

  This element is reserved for those problems where adequate procedures do not appear to exist to preclude and/or detect their occurrence. The problems appearing in this element should be candidates for new technology.

* <u>Failure to Follow Specifications</u>

  Human errors, in spite of adequate instructions, procedures or criteria, are included in this element. These problems are segregated with the thought that they are somewhat inherent and could not be readily addressed (reduced).

These Factor Elements contribute to the Manufacturing and Quality Control Causal Factor as shown in Figure 14.

<u>Discussion of Results for Manufacturing and Quality Control</u>

Since the total Manufacturing and Quality Control factor is small, it is to be expected that any further breakdown would result in nearly insignificant values.

Only the Alternate Assembly/Quality Control Procedures Not Available element provides any conclusion of real interest where one failure mode - Compressor Blade/Disc Fatigue - dominates. Here, a real need exists to develop inspection techniques for the material integrity or consistency of compressor discs.

The Failure to Follow Specifications element consists of both basic material specification noncompliance and assembly/manufacturing errors such as welding operations.

No major conclusions seem to emerge from this Factor Element.

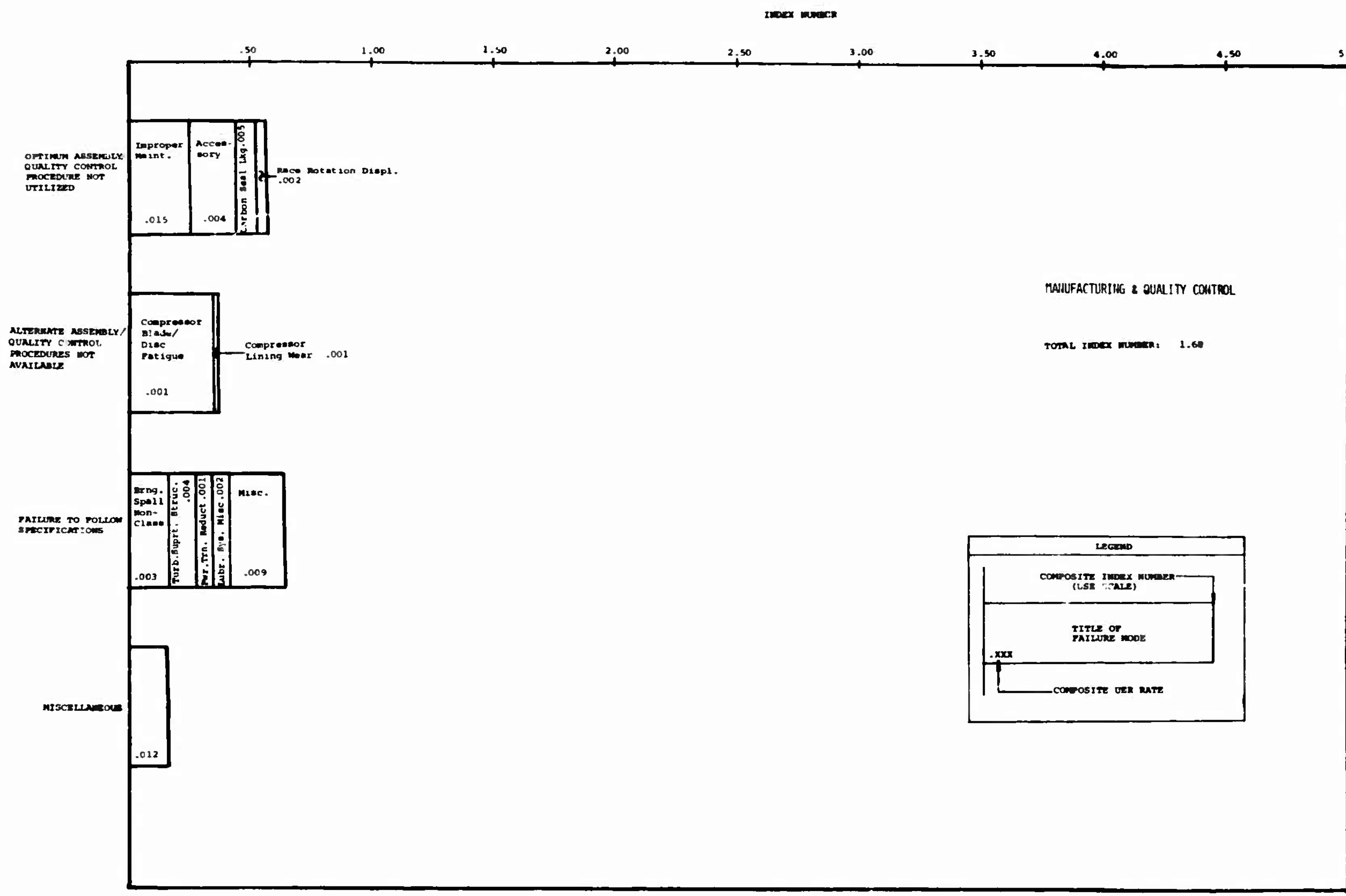

Figure 14. Factor Elements for the Manufacturing and Quality Control Causal Factor.

OPERATIONS AND MAINTENANCE

This Causal Factor is assigned those problems that originate in the in-service operation and maintenance of the engine. Problems are assigned to this Causal Factor only when reason-able design activities could not have precluded the problem. The contribution of Operations and Maintenance to the total problem is shown in Figure 15.

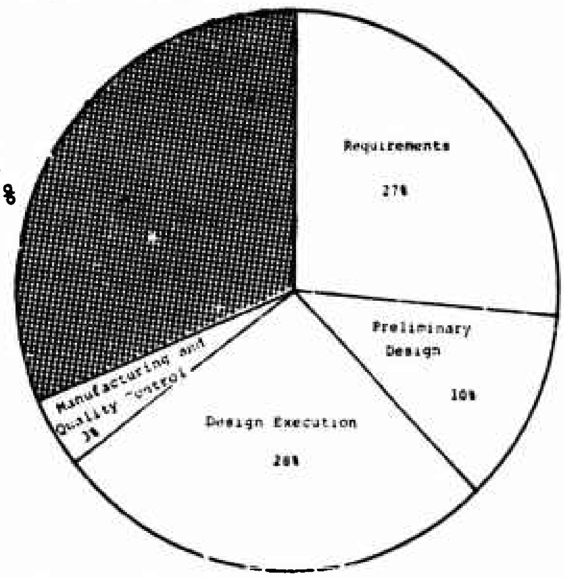

Figure 15. Contribution of Operations and Maintenance.

The Factor Elements for this Causal Factor have been defined in order to provide easy identification of remedial action. The Factor Elements are:

- <u>Avoidable Operation of Engine/Aircraft Outside Limits</u>

  This, as the only one of two operator-oriented Factor Elements, includes all problems that appear to be reasonably avoidable in the operation of the engine/aircraft. Problems in this element are due to clear and avoidable violations of established procedures and/or criteria. Not included in this Factor Element are those operator-related problems which do not appear to be avoidable; for example, periodic over-stress of an engine due to an emergency condition.

- <u>Maintenance Criteria - Ill-Defined</u>

  This element is designed to isolate those maintenance-related problems which are directly traceable to

inadequate removal, repair, or troubleshooting procedures and criteria.

- Maintenance Damage

  This element is reserved for those problems caused by maintenance where no specific procedures could be shown to be inadequately defined. In other words, this element is those mistakes that are made that are a complex function of individual skill and morale and could not be reasonably improved through changes in specific manuals, availability of tools, etc.

- Optimum Logistics Program - Not Utilized

  This element is reserved for the single problem of engines removed by cannibalization and includes most of those removals classified in the Convenience failure mode. This element is separately identified so that the effects of improved logistics management can be identified.

- Inadequate Diagnostics Technology

  This element includes those problems that arise from engine malfunctions not being detected accurately or in sufficient time.

- Normal Operations/Maintenance Environment

  This element includes those problems which appear to be inherent in the operations and maintenance of engines in the military service. The suggestions implied in the creation of this Factor Element is that no remedial action could be applied to these portions of the various problems.

These Factor Elements contribute to the Operations and Maintenance Causal Factor as shown in Figure 16.

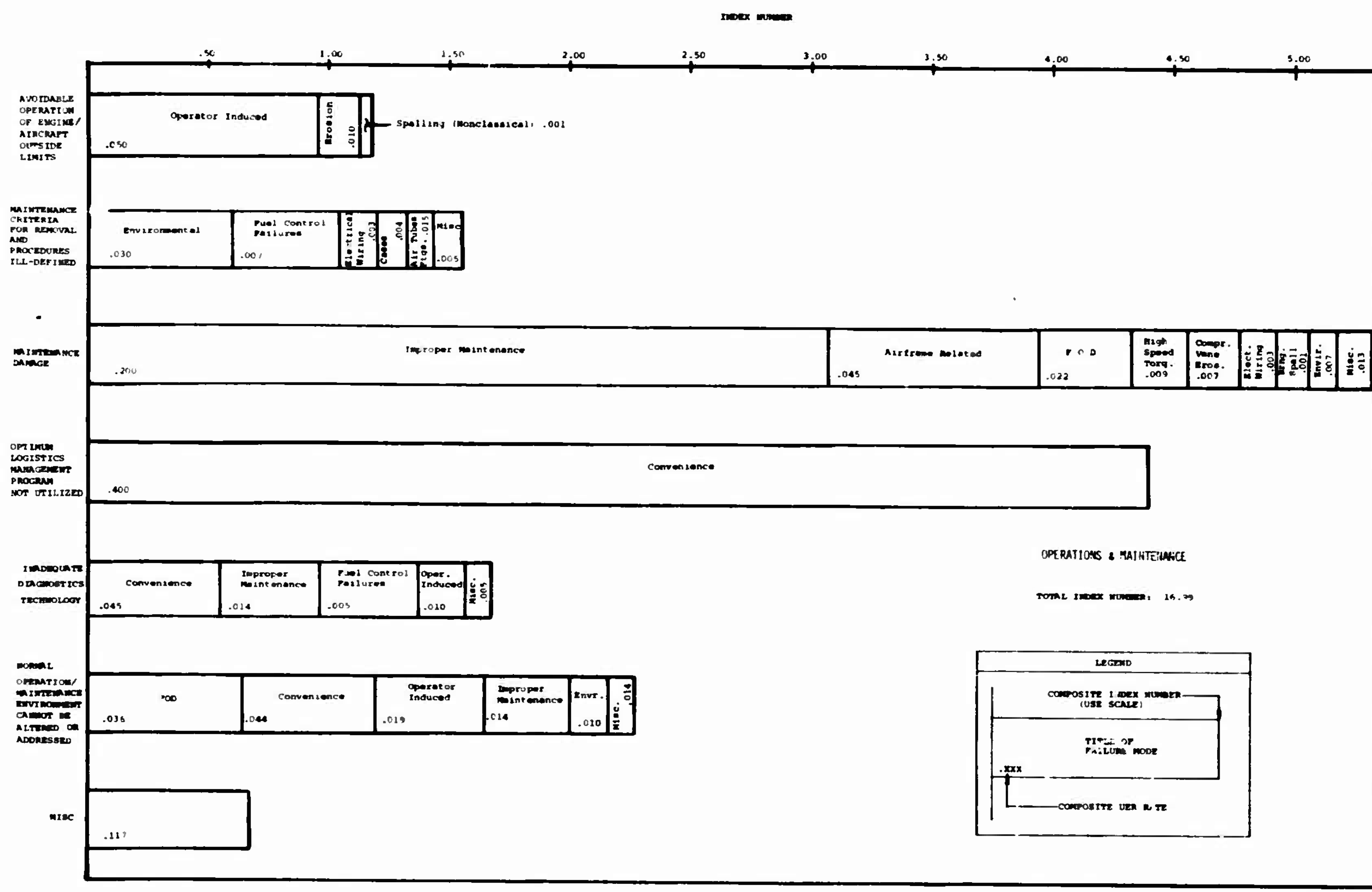

Figure 16. Factor Elements for the Operations and Maintenance Causal Factor.

Discussion of Results for Operation and Maintenance

The only meaningful Factor Element addressing the operator portion of Operations and Maintenance (avoidable operation of engine aircraft outside limits) is only 7% of the total but is still a rather large absolute value of a problem source and, to the extent that much of this rate is avoidable, remedial action should be appropriate. Of much more importance are the next four factor elements primarily relating to the maintenance aspects of engines. The maintenance criteria element should warrant particular attention since maintenance manual improvement is the logical remedial action for these problems. Of dominating concern, however, is the single highest Factor Element of maintenance damage. Previous studies[1] have shown that maintenance damage is a problem of similar magnitude in the three military services and is at least ten times that which had been experienced in commercial airline service. Since it is believed that this problem is due to a general morale and training condition, concern that this problem will increase in the future should be one of the prime considerations of those attempting to reduce the O&M cost of military systems. Inadequate logistics management is the second highest single Factor Element and reflects undoubtedly the operational environment of the majority of the engines examined (combat operations in Southeast Asia). Nevertheless, the unnecessary manpower and cost associated with the unavailability of spare engines should be considered unacceptable. The impact of inadequate diagnostics technology appeared as surprisingly small. This either may be due to the relative weakness of maintenance man-hours as a contributing parameter to the Index Number or may be due to the authors' conservatism as to the potential benefits of further diagnostics systems.

In general, the pattern that emerges after examining the Factor Elements in Operations and Maintenance is not an encouraging perspective. The few Factor Elements which are susceptible to effective remedial action are relatively small. The Factor Elements which require more general and therefore expensive remedial actions appear to dominate the Causal Factor of Operations and Maintenance. On the other hand, this pessimistic outlook should be modified by the acknowledgement that several of the failure modes that are assigned to this Causal Factor (improper maintenance, convenience) are directly related to the basic removal rate (reliability) of the engine. These relationships are clearly shown in Reference 1.

RESULTS OF REMEDIAL ACTION ANALYSIS

IDENTIFICATION AND QUANTIFICATION OF REMEDIAL ACTIONS

The identification of potential remedial actions arises from the Causal Factor analysis discussed in the preceding section. By separating the specific causes of problems, remedial actions emerge naturally. The procedure for identifying and quantifying the benefit of remedial actions was to examine the contribution of each failure mode to each Causal Factor and Factor Element and to list those remedial actions which were appropriate. An example of this analysis is shown in Figure 17. The complete results of this analysis are given as Appendix I.

TABLE XXVII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: GENERAL LACK OF R&M EMPHASIS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	.51 / 5.09	.031 / .305	Give greater consideration to maintainability durability	Particular	T58 Total Removal Rates	T74 Total Removal Rates	2.55	.15	3.50	.020
			(Emphasis on R&M in requirements)	Composite	50% of experienced range	10% of experienced range	.85	.05	.17	.01
Power Train Reduction	.29 / .72	.005 / .013	Require higher reliability in gearbox bearings and seals	Particular	50% eff on worst rate	20% eff on best rate	.39	.007	.05	.001
			(Emphasis on R&M in requirements)	Composite	80% improvement	20% improvement	.20	.004	.05	.001
Operator Induced	.25 / 2.54	.012 / .122	Give greater consideration to engine and operations	Particular	T63 rates 100% improvement	Smallest rates 40% improvement	2.52	.120	.084	.004
			(Emphasis on R&M in requirements)	Composite	100% improvement	40% improvement	.25	.012	.100	.005

Figure 17. Example of Analysis Sheet for Identification and Quantification of Remedial Actions.

This type of analysis sheet was prepared for each Factor Element in each Causal Factor as indicated at the top of each sheet.

The following paragraphs describe the various portions of this analysis sheet.

Failure Mode - Failure modes which were identified as having

a contribution from this Factor Element are listed in descending order of Index Number value.

Composite - The values of Index Number and Unscheduled Engine Removal (UER) for each failure mode as they contribute to the Composite engine are shown as a set. The upper value is the contribution of the specific Factor Element to the total rate for the mode, and the bottom value is the totol rate for the mode.

Potential Remedial Action - Candidate remedial actions are listed with a remedial action group also identified (in parentheses). These groups allow meaningful summarization of remedial actions in subsequent portions of the study. Where more remedial actions than one are identified, they are considered independent of each other unless otherwise noted.

Engine Baseline - This indicates the engine baseline against which the remedial action is quantified. There are two types of baselines noted - Composite and Particular. Where the Composite baseline is noted, remedial actions are applied against the values (Index Number and UER) of the Composite engine as reported in Reference 1 and summarized in the introductory section of this report. Where the Particular baseline is noted, remedial actions are applied (quantified) against the values, again both Index Number and UER, of engines whose experience in this failure mode was particularly high or particularly low.

Assumptions - These columns indicate the specific engine, configuration, or other suppositions that were used in quantifying benefits of the remedial action. The Assumptions column is divided into Maximum and Minimum columns. On the Particular baseline, the Maximum column describes the engine or configuration against which the remedial action provides the highest numerical benefit, and the Minimum column corresponsingly represents that engine, configuration, etc., which would provide the least numerical benefit of the remedial action. On the Composite baseline, the Maximum and Minimum columns usually represent merely varying levels of effectiveness of the remedial action against the composite baseline value of the problem.

Maximum and Minimum - These columns include the quantified benefit of the remedial action for both Index Number and UER that correspond to the Engine Baseline and Assumptions indicated.

SUMMARIZATION OF REMEDIAL ACTIONS

With each failure mode examined for potential remedial actions, all similar remedial actions are grouped together and their benefits added. Frequently, the same remedial actions are applied against several failure modes, and this summarization serves to indicate the total effect of a specific action independent of failure modes. Similar remedial actions are further summarized in groups and subgroups in Table VIII.

TABLE VIII. REMEDIAL ACTION GROUPS

GROUP SUBGROUP
Testing
Basic Test Configuration/Type
Addition Duration
Test Execution
Specimen Variability
Improved Technology
Development of New Materials/Designs
Effects of Normal Operations
Effects of Degraded Conditions or Variations in Normal Conditions
Diagnostics Technology
De-emphasis on Performance/Weight
Utilization of Axial/Centrifugal Over Axial Flow Compressors
Specify Labyrinth Seals
Provide Adequate Low-Cycle Fatigue Life
Requirement for Specific Features
Require Inlet Particle Separators
Require Inlet Protection Screens
Improved Maintenance
General Improvement in Skill and Care
Better Definition of Inspection Techniques, etc.
More Complete Failure Criteria
Control of Design Configuration/Arrangements/Materials
Require Electrical Torquemeter
Specify Bearing Positive Retention
Preclude Use of Rear-Drive Engine
Use Most Corrosion Resistant Materials
Use Elliptical Outer Face Bearings
Increased Use of Analytical Procedures
Configuration/Design Lessons/Interfaces
Consideration of Normal Conditions
Consideration of Abnormal Conditions
Decrease in Functional Requirements
Elimination of Power Management Systems
Eliminate High-Speed Output
Improved Logistics Management Program
General Emphasis on R&M in Requirements
Additional Consideration of Maintenance Durability
Additional Consideration of Helicopter Environment
Greater Consideration of Operation on Engine/Aircraft
Require Higher Levels on Gearbox, Bearings and Seals
Require Higher Levels on Main Shaft Bearings
Provide Greater Flexibility in Scheduling
Additional Control of Engine/Airframe Interface
Insure Access to all Components
Specify Close Location of Screens
Specify Pod-Mounted Engines
Provide Adequate Control Protection Devices
De-emphasis on Acquisition Cost
Preclude Use of Pneumatic Fuel Control
Require Integrally Cast Nozzle Assembly
Additional Quality Control Effort
Closer Control of Operation of Engine
Improvement in General Operations
Control Aircraft Exposure to Extreme Environments
Adhere to Engine Shutdown Procedures

Each specific remedial action is classified into these groups on sheets entitled Summarization of Remedial Actions. An example of these sheets is shown below in Figure 18, with the complete results provided in Appendix II.

TABLE XLIX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Test Using a Spectrum of Manufacturing/Assembly Tolerance Variations	Combustion Liner Cracking Warping	Design Execution - Inadequate technology	Particular	.81	.027	.45	.015
			Composite	.17	.006	.10	.003
	PARTICULAR SUBTOTAL			.81	.027	.45	.015
	COMPOSITE SUBTOTAL			.17	.006	.10	.003
Test With Extremes in Variability	Combustion Swirl Cup Problems	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.40	.05	-	-
			Composite	.09	.007	.05	.002
	PARTICULAR SUBTOTAL			1.10	.05	-	-
	COMPOSITE SUBTOTAL			.09	.003	[illegible]	.002
TOTAL (SUBGROUP)	PARTICULAR			17.73	.837	2.25	.022
	COMPOSITE			3.25	.054	2.21	.027
TOTAL (GROUP)	PARTICULAR			91.22	3.269	6.85	.330
	COMPOSITE			17.55	.636	7.53	.301

Figure 18. Example of Sheet for Summarization of Remedial Actions.

The results of this summarization process are shown below in Table IX in tabular form and in Figures 19 and 20 in graphical form, where the remedial action groups are prioritized by their Index Number benefit. Only the maximum benefit values for both Index Number and UER rates are shown on Table IX and in Figures 19 and 20. Figure 19 describes the benefits of the remedial action groups against the basic Composite engine, and Figure 20 describes the benefits against a Particular engine with the basic Composite benefit also noted as shown in the legend. Table IX includes both Composite and Particular engine benefits.

TABLE IX. QUANTIFICATION OF REMEDIAL ACTION MAJOR GROUP

Remedial Actions	..ximum Benefit			
	Composite		Particular	
	Index	UER	Index	UER
1. Testing	17.55	.636	91.22	3.269
2. Improved Technology	10.03	.399	14.96	.540
3. De-emphasis on Performance/Weight	9.67	.525	210.79	10.301
4. Requirement for Specific Features	5.07	.298	219.59	11.200
5. Improved Maintainence	4.32	.292	4.32	.292
6. Control of Design Configuration/ Arrangement/Materials	3.75	.164	19.43	1.101
7. Increased Use of Analytical Procedures	3.16	.145	23.78	1.019
8. Decrease in Functional Requirements	2.62	.075	15.61	.435
9. Improved Logistics Management Program	2.20	.200	13.20	1.200
10. General Emphasis on R&M in Requirements	1.87	.078	6.56	.255
11. Provide Greater Flexibility in Scheduling	1.26	.016	3.60	.047
12. Additional Control of Engine/Airframe Interface	1.20	.052	28.71	1.245
13. De-emphasis on Acquisition Cost	1.08	.026	9.78	.222
14. Additional Quality Control Effort	.72	.041	2.04	.085
15. Closer Control of Operation of Engine	.70	.036	2.35	.077

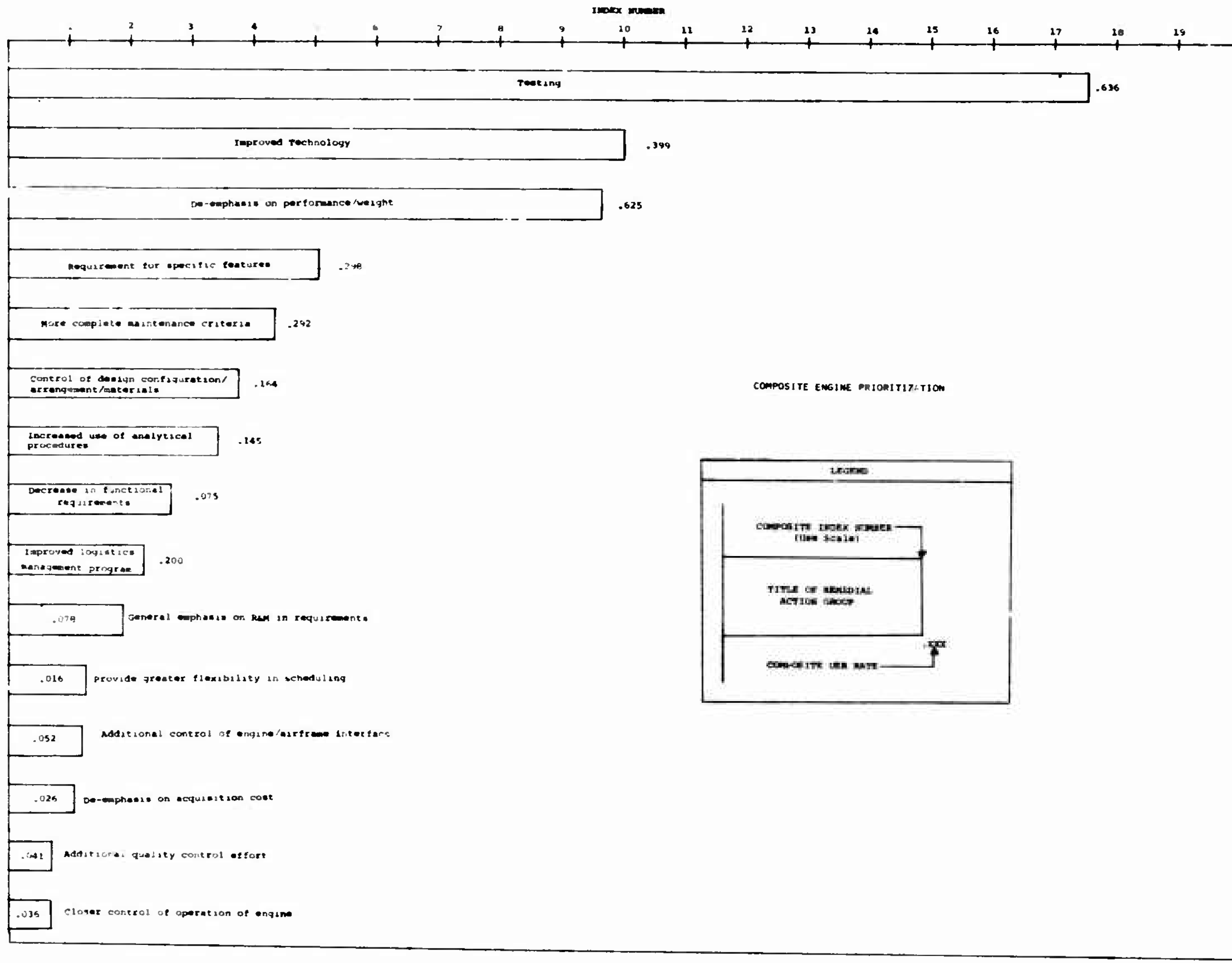

Figure 19. Prioritization of Remedial Action for Composite Baseline.

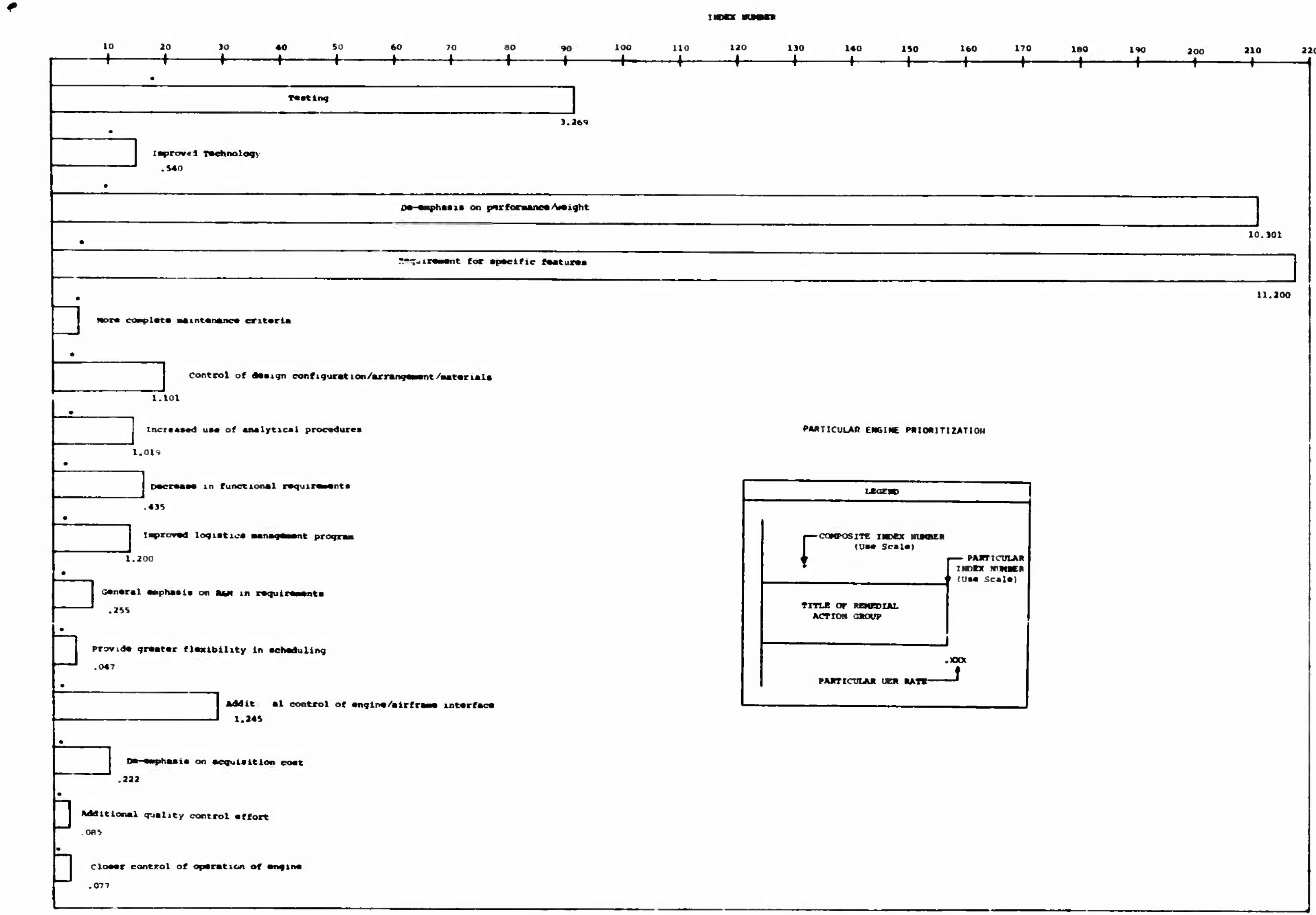

Figure 20. Prioritization of Remedial Action for Particular Baseline.

DISCUSSION OF SUMMARIZATION

Composite Versus Particular Ranking

The most significant observation that emerges when comparing the Composite and Particular engine prioritization is the significant changes in rank ordering of several remedial action groups.

The groups of De-emphasis on Performance/Weight and Requirements for Specific Features, which are ranked second and third respectively when viewed against the Composite baseline, emerge as the second and first group when viewed against a Particular engine baseline. Where they were previously approximately one-half of the benefit of the Testing group, they are over twice as large as Testing in the Particular framework.

Another remedial action group whose ranking is significantly affected when examining the Particular engine prioritization as opposed to the Composite engine is the group of Additional Control of Engine/Airframe Interfaces. This group, ranked twelfth out of the total of fifteen groups, rises to fourth priority in the Particular prioritization.

The common characteristic of these three remedial action groups which have such a great potential for significant R&M improvements on future engines is that all pertain to the activities relating to a specific engine development program and generally are achieved early in the specification stage for each specific engine. As such, the role of the customer in achieving these benefits is prime.

A prioritization against a Particular engine baseline, as explained in earlier sections, is more risk avoidance on a specific engine than general Army wide R&M improvement requirement. While this distinction is subtle, it is nonetheless important; the most common question that arises is usually, "What should we do on this engine that we are responsible for?", and the prioritization against the Particular engine addresses that question.

General Ranking

Testing, as a remedial action group, is large on either prioritization process. On the Composite engine, prioritization of the testing group is nearly twice as large as the second and

third ranked groups. Subsequent discussion of testing will address the specific actions that must be accomplished to realize these benefits.

The second highest ranked remedial action on the Composite is Improved Technology. It is a remedial action of a general nature which can address any engine program and whose magnitude of potential benefit dictates the most intensive examination.

The fact that Improved Technology as a remedial action group did not increase significantly with a Particular baseline should not be allowed to be deceptive. Remedial actions of a general nature such as Improved Technology and Improved Maintenance do not relate to decisions directed against a specific engine. It was not considered appropriate, therefore, that the potential benefit on a Particular engine be quantified for this type of remedial action. If the dramatic effects of considering Particular engines were applied to the Improved Technology group, it would increase in magnitude to a point where its relative ranking on the Composite display would be maintained.

De-emphasis on Performance/Weight is ranked third and is intimately related to the requirements established for each specific engine. Control implementation is, therefore, in the hands of one group of decision makers. This ease of control (as opposed to more general remedial actions, such as Improved Technology) and the large magnitude of potential benefits require that attention be directed at this source of R&M improvement.

Requirements for Specific Features, fourth on the Composite ranking and first on the Particular ranking, is even more a directly controllable remedial action and, as will be shown later, consists of only a few specific decisions. When all these factors are considered, this action should be, so to speak, the "first order of business" in establishing the requirements for a new engine application.

The other remedial actions fall off rapidly in potential benefit. Despite their smaller numerical benefit, however, many of the remaining actions warrant examination. In many cases the lack of a "penalty" (cost, weight, performance, development time or cost, etc.) when incorporating these remedial actions causes them to be as attractive as the actions with more dramatic benefits.

The next section discusses each remedial action in detail.

DISCUSSION OF REMEDIAL ACTIONS

Each of the fifteen remedial action groups is discussed in detail in this section and is addressed in the order that it ranks on the Composite engine prioritization. The discussion for each remedial action group will include the following:

- Further identification of remedial action subgroups and/or failure modes that are affected by the remedial action(s).
- Displays indicating the benefits against both the Composite and Particular engine baselines.
- Technical discussion of the action in terms of past or potential effectiveness, cost of achievement, current status, verification methods, etc.
- Program discussion directed at identifying where in the engine development cycle the action must be initiated and sustained, who is responsible for the activity, and means by which the action may be monitored.
- Recommendations

Testing

The remedial action group of Testing is one in which subgroups were established. These subgroups are:

Improved Test Execution

This category is intended to represent those remedial actions which can be accomplished within existing frameworks of test types and durations. This implies that this subgroup is more under the control of the contractor than the other subgroups, which are primarily the direct result of stated customer requirements with appropriate funding and scheduling considerations.

Expanded Basic Test Configuration/Type

This subgroup represents the benefits that can be achieved when the developmental tests are expanded in terms of the basic loads component interfaces. This expansion implies an increase in cost and/or time of such a level that customer direction would normally be required for implementation. It is unrealistic to expect contractor initiative alone to be adequate to achieve these benefits.

Greater Use of Specimen Variability

This subgroup isolates the benefits that could be achieved when greater use is made of the inevitable variability in component material properties, physical dimensions, or operation characteristics. The benefit represents those problems which could be eliminated or minimized when a conscientious effort was made to incorporate these variations in the specimens under test.

Additional Duration

Since many of the R&M problems in mechanical equipment are of a probabilistic nature, additional exposure is required to detect certain problems. This subgroup is reserved for those types of problems. Within the Testing group, this subgroup of Additional Duration was used only as a last consideration. Certainly Additional Duration would increase the number of times that problems would be detected and would naturally achieve benefits such as more exposure to specimen variability. However, Additional Duration requirements were considered only when other test improvement techniques would not have been successful.

These subgroups contribute to the total testing groups as shown in Table X, where the maximum benefit is shown for the Composite and Particular engine baselines for both the Index Number and UER parameters. These values are shown in graphical form in Figure 21 for the Composite engine and in Figure 22 for the Particular engine.

TABLE X. REMEDIAL ACTION SUBGROUPS FOR TESTING

Remedial Actions	Maximum Benefit: Composite Index	Composite UER	Particular Index	Particular UER
Improved Test Execution	7.41	.354	25.89	1.049
Expanded Basic Test Configuration/Type	4.48	.176	21.49	.855
Greater Use of Specimen Variability	3.25	.054	17.73	.837
Additional Duration	2.41	.052	26.11	.528
Total	17.55	.636	91.22	3.269

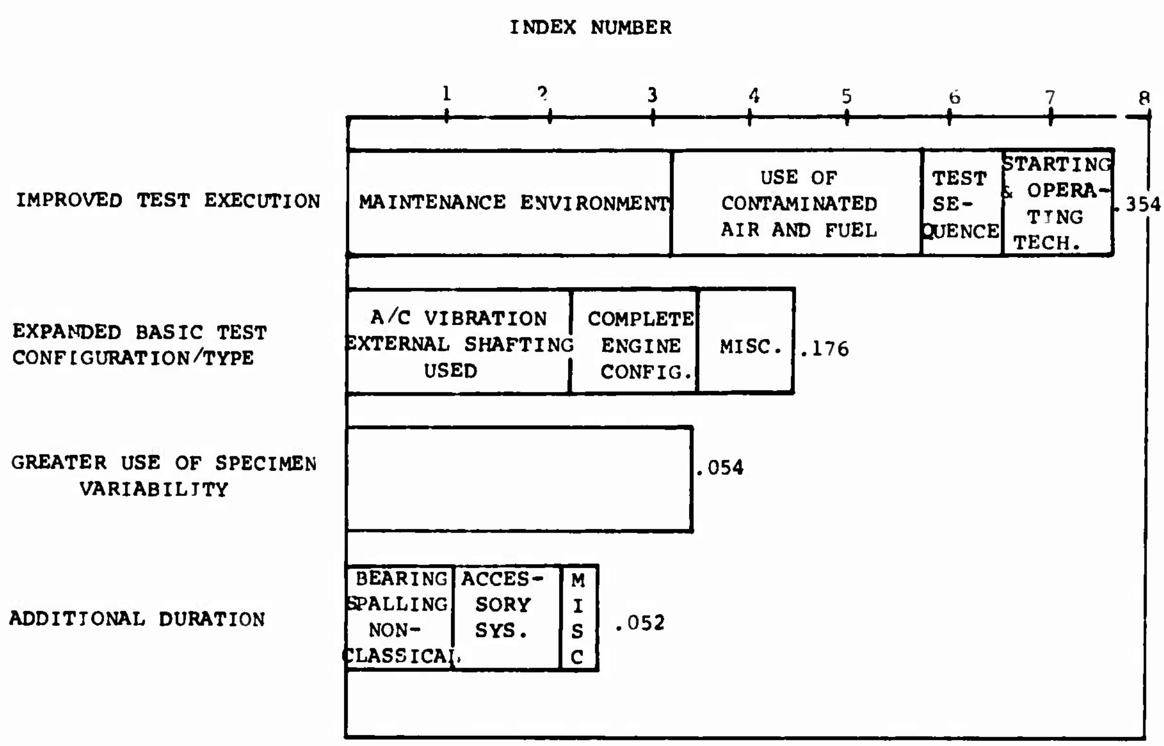

Figure 21. Remedial Action Subgroups for Testing for Composite Baseline.

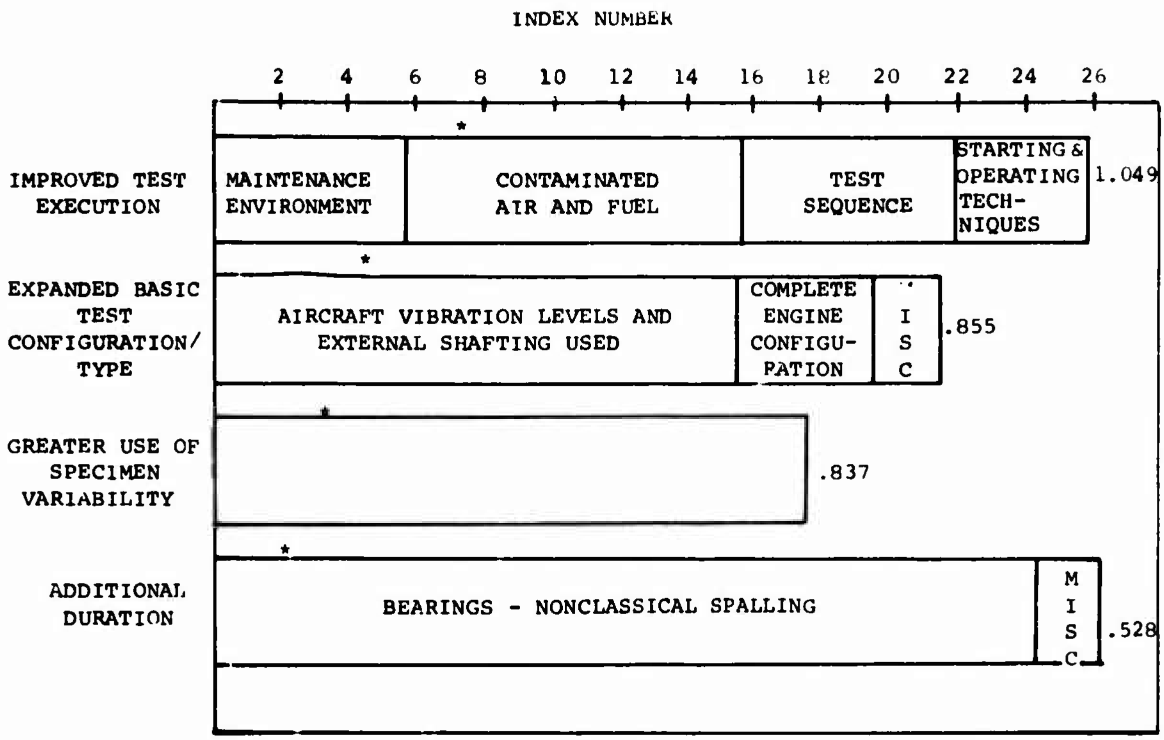

Figure 22. Remedial Action Subgroups for Testing for Particular Baseline.

The most significant difference in rank ordering for the Testing subgroup between the Particular and Composite baselines is the increase in rank of the Additional Duration subgroup. As shown on Figures 21 and 22, it is primarily the main shaft bearings which on a particular engine could have such a high failure rate that Additional Duration would be the most beneficial remedial action. Aside from this change in ranking, the other three subgroups maintain the same rank order in both the Composite and Particular engine baselines.

Improved Test Execution is ranked first on the Composite baseline, nearly twice as large as the other three subgroups. Even on the Particular engine baseline where Additional Duration ranked first, Improved Test Execution is a close second. The four divisions of Improved Test Execution shown on both Figures 21 and 22 are designed to indicate the nature of the improved execution required.

The Maintenance Environment division indicates that the benefit of realistic maintenance procedures and skills were applied to the test program and responsive corrective action initiated

when maintenance-induced problems were revealed. The tradition of "tender loving care" during development test is inappropriate when viewing the historical inevitability of these types of problems across all engine configurations, operating environments, military services. The Greater Use of Contaminated Air and Fuel division contributes a significant portion to the benefit of this subgroup. Increased application of these abusive conditions may be viewed by some as requiring specific customer direction and, therefore, should not be assigned to this subgroup of Improved Test Execution. However, the authors believe that in a test program where the emphasis is on developmental exploration of engine reliability, modest increases in the use of contaminated air and fuel are well within the c[illegible]tor's authority and, indeed, responsibility. The Test Seq[illegible] division relates to the order in which tests are perfo[illegible] and the engine specimens utilized in this sequence. One of the specific failure modes which would be the primary beneficiary of this type of remedial action would be erosion/corrosion-induced fatigue failures of compressor vanes. If extended running were performed after erosion tests were performed, the fatigue life of compressor vanes in a partially eroded state could be determined. This division of remedial action did not appear to impose any significant cost or scheduling penalties.

Use of expected Starting and Operating Techniques during the test program can uncover many problems which have heretofore been uncovered only during operational use. Recent trends in developmental test planning have addressed this area, and it would be expected that with the proper developmental environment, much of these benefits would be achieved without an extensive additional effort.

The subgroup of Expanded Basic Test Configuration/Type is broken down into two divisions which represent the inherent limitations of existing bench tests. The division of Aircraft Vibration and External Shafting Used represents those problems whose solution will require either additional aircraft flight testing or a significant escalation in the complexity of existing test stands. While some engine test programs have been operated for periods where an assumed aircraft vibration level was imposed on the engine while operating, the cost and schedule implications of this complexity suggest that aircraft flight testing would be a more cost effective approach. This would obviously require complete customer involvement in terms of the funds and time for such a significant change over existing programs where only token flight testing is performed.

The division of Complete Engine Configuration relates to problems previously undetected until the complete engine installation was tested. Frequently engine developmental test programs concentrate on the basic power generation and extraction core and utilize breadboard fuel, oil or accessory systems. Whether complete engine configurations can realistically be achieved during bench testing is debatable. What is certain, however, is that bench testing will require careful customer and contractor planning with, again, funding and schedule recognition.

The subgroup of Greater Use of Specimen Variability is not broken down into any divisions or failure modes. Detailed examination of past R&M problems has indicated that all engine subsystems have been affected by subsequent variations in material properties, part dimensioning and manufacturing techniques. Although specimen variability is naturally achieved through the use of additional specimens that accompany extended durations, specific action by the development team to utilize components at the extremes of their allowable variations is the activity required to achieve the full benefits so indicated and would appear to require active customer participation.

The whole question of development testing - its purposes, potential and state of art - is not well understood. Many factors contribute to the confusion. In a study for the Air Force on all aspects of the Air Force Engine Maintenance Program by ARINC Research Corporation, some of these factors were examined, with the conclusion, "The assumption that the qualification test was a single 150-hour endurance run that yielded a '150-hour engine' was the largest single problem in misunderstanding of the engine qualification test".[2] The report also discussed the limitations of bench tests to improve or demonstrate reliability and recommended that studies be performed to define the cost effectiveness of integrated airframe/engine testing even if this testing delayed production.

This same emphasis on improving the execution of development tests emerged in another study of the engine acquisition process conducted by a joint Army/Navy/Air Force task force. After recognizing the importance of an adequate amount of testing, the report added that "the quality of the testing is of equal importance", and concluded that "the military services must do more in the area of designing tests...."[3]

---

[2] A STUDY OF THE AIR FORCE JET ENGINE MAINTENANCE PROGRAM REPORT, ARINC Research Corporation, 30 May 1970.

[3] A STUDY OF THE AIRCRAFT ENGINE ACQUISITION PROCESS, Joint AMC/NMC/AFCC/AFSC Commanders' Panel on Aircraft Engine Acquisition, 5 February 1971.

Clearly this testing area should receive more attention in the form of analysis that could allow realization of these potential benefits.

Improved Technology

The remedial action group of Improved Technology is also one in which subgroups were established. These subgroups are:

Development of New Materials and Designs

This subgroup is reserved for those benefits that could occur through the development of actual materials or design concepts which would be used for the prime functions of power generation, extraction and transfer. This definition excludes from this subgroup the development of hardware which would be used in a supportive role such as diagnostics or quality control activities.

Improved Ability To Consider Effects of Degraded Conditions or Variations in Normal Conditions

This subgroup represents the benefit that could arise from development and application of analytical skills as opposed to hardware development. The analytical procedures that are considered in this subgroup are those which relate to the effects on engine reliability due to degraded or significant variations in the normal operating condition of the engine.

Improved Diagnostics Technology

This subgroup includes the benefits from the development of both Improved Diagnostics hardware and software.

Improved Ability To Consider Effects of Normal Operation

This subgroup, like the second subgroup, is basically the improvement in analytical capabilities. In this subgroup the issue is the ability to handle the load and temperature effects of normal operation.

Improved Quality Control

The development of new techniques or approaches to the assurance of adequate quality is considered in this subgroup. Only benefits that could not accrue unless additional technology was developed are included. In other words, the benefits of more complete application of existing techniques or general improvements in thoroughness are not included.

These subgroups contribute to the total Improved Technology group as shown in Table XI, where the maximum benefit is shown for both Composite and Particular engine baselines for both the Index Number and UER parameters. These values are shown in graphical form in Figure 23 for the Composite engine and in Figure 24 for the Particular engine.

TABLE XI. REMEDIAL ACTION SUBGROUPS FOR IMPROVED TECHNOLOGY

	Maximum Benefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Development of New Materials/Designs	6.49	.250	7.27	.279
Improved Ability To Consider Effects of Degraded Conditions or Variation in Normal Conditions	1.22	.025	1.22	.025
Improved Diagnostics Technology	1.10	.097	1.10	.097
Improved Ability To Consider Effects of Normal Operations	.97	.025	4.68	.093
Improved Quality Control	.25	.002	.69	.046
Total	10.03	.399	14.96	.540

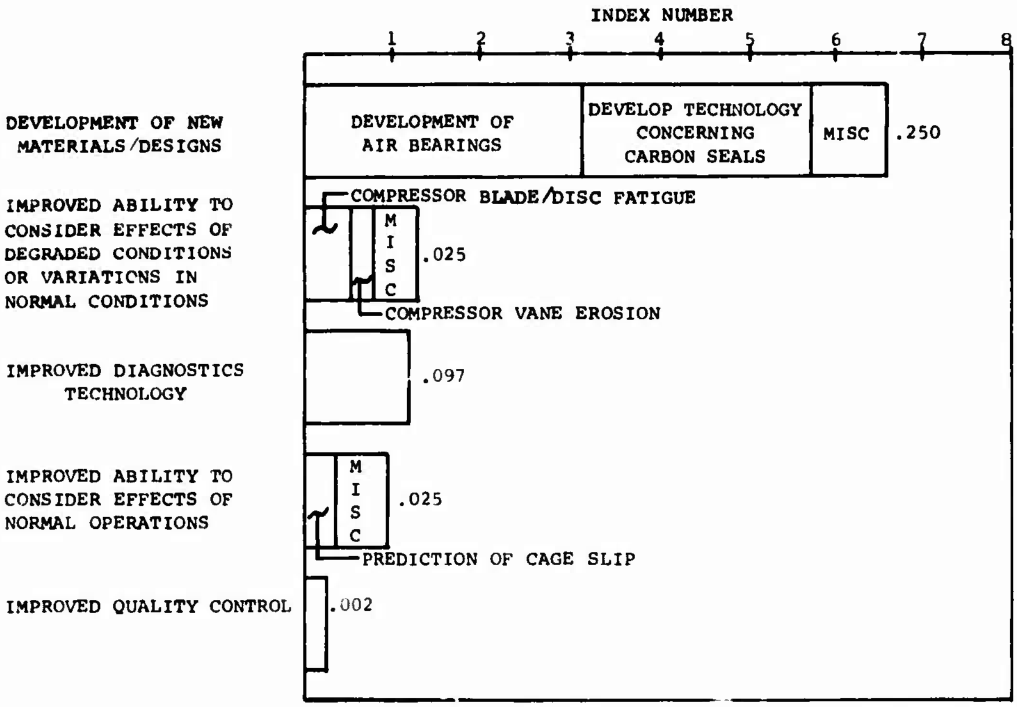

Figure 23. Remedial Action Subgroups for Improved Technology for Composite Baseline.

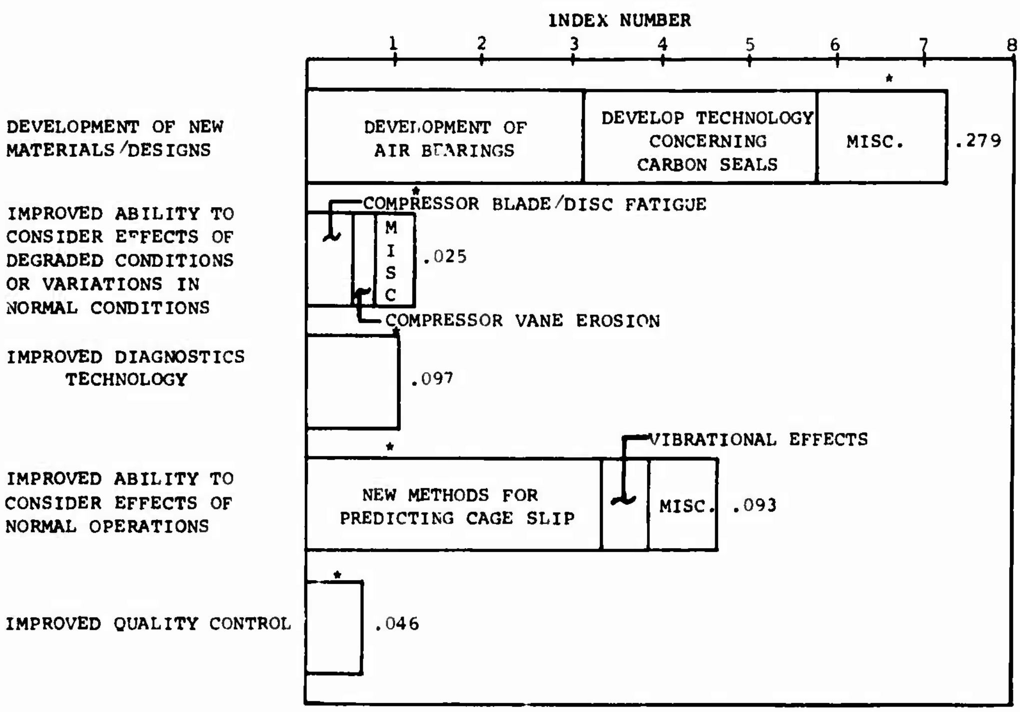

Figure 24. Remedial Action Subgroups for Improved Technology for Particular Baseline.

The only significant difference in the Composite and Particular displays of Improved Technology subgroups is the large impact of the subgroup termed Improved Ability to Consider Effects of Normal Operation. Other than this change, both rank ordering and absolute value of benefit of the various subgroups do not change significantly.

The subgroup of the Development of New Materials/Designs clearly dominates the Improved Technology group and primarily consists of potential benefits in the two areas of bearings and seals. The successful development of air bearings could produce a benefit greater than any one of the lower eight remedial action groups (see Figure 20). The precise status of this development is not clear to the authors. Reference 4 appeared to present an encouraging potential for air bearings for main shaft applications, and that position should be qualified. Air bearings could provide relief from the many failure modes inherent in rolling element bearings.

Similarly, the development of reliable carbon or other positive sealing devices would have a significant benefit. The benefit calculated for reliable positive contact seals assumes conservative running speeds (250-300 feet per second). If carbon seals were utilized with speeds higher than these values, the potential benefit could be even greater. This development of reliable carbon seals is not intended to represent only the traditional circumferential and face type carbon seal used in past engine designs. Its benefit is meant to indicate the value of the successful development and application of any positive or close contact seal. A variety of configurations currently under development and installed in new engines appear to meet that test and may have achieved the benefits so indicated.

The role of the military community can be significant by either assuring that these two developments are complete or, if their technology is currently adequate, providing that information to the engine design community.

Normally, when the state-of-the-art materials are considered in gas turbine engines, reference is usually made to the high-speed rotating elements and more particularly the high-temperature turbine applications. These areas have been traditionally considered the prime candidates for advancements in new materials. Materials, metals or nonmetals, that withstand higher operating temperature and possess greater thermal stability and general strength at elevated temperatures along with new

---

[4] Paladina, W., STATIC AND ROTATING AIR/GAS SEAL EVALUATION, Curtiss-Wright Corporation, USAAMRDL Technical Report 71-28, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, June 1971, AD730361.

cooling techniques in turbine blades and vanes have allowed higher turbine temperatures and greater engine efficiency. These benefits have driven the historical emphasis in these areas. Future development of new materials possessing further advantages will continue to allow even higher operating temperatures and greater efficiencies. However, the limits of existing materials and these new materials are, and will be, well recognized by the design community. These new materials are invariably used to realize performance advantages and are rarely, if ever, used for reliability gains. It is for this reason that the future development of materials and designs in compressor blades and discs, combustion systems, turbine wheels, blades and vanes does not appear as significantly contributing to a reliability benefit on Figures 23 and 24.

The subgroup of Improved Ability To Consider Effects of Degraded Conditions or Variations in Normal Conditions is, as indicated earlier, not a hardware but an analytical capability. The benefits of this subgroup are largely due to compressor components. The blade/disc fatigue portion results from an increased ability to consider unusual aerodynamic intake conditions, dimensional variations in the tenon area, material variations (particularly of cast assemblies), and the potential for resonant conditions under varying speed and/or loading conditions. The vane erosion portion reflects an ability to understand how vane resonances would change under partially eroded conditions. The magnitude of the benefit of this subgroup is driven primarily by the accidents caused by compressor problems with their associated sudden loss of power. The small UER rate associated with this remedial action reflects that the Index Number is strongly influenced by the accident rate and the TBO parameters. Much attention has been directed at this analytical capability due to problems in past engines. Much of this technology is considered to be highly proprietary by the engine manufacturers and appears to be rapidly progressing although not summarized in any one source.

The customer's role in achieving the benefits of this subgroup, particularly for those compressor-related benefits, could be to fund an effort that would collect this technology and through the dissemination of this technology insure that all engine manufacturers benefit from the separate activities of each. This type of general research could benefit turbine engine reliability across all models. On specific engine development programs it is difficult to assure that this technology is incorporated except through testing programs.

Adequate control prior to these tests would be virtually impossible.

Improved Diagnostics Technology is a subgroup which consists of improvements in both the prognostics and the fault isolation capabilities of diagnostics systems. These are two different characteristics which affect different subsystems and failure modes and arise from different technologies. The prognostics capability requires a time prediction of when failures or degraded conditions will progress to the point where an unscheduled action will be required. The problems addressed by improved prognostics are convenience removals and operator induced and erosion problems and contribute two-thirds of the benefit shown. Improved troubleshooting or fault isolation capabilities relate to the ability to confirm that a failure has occurred and which specific component or module must be repaired/replaced. Improvements in this area affect fuel control failures, which cause removals, improper maintenance, and turbine coupling failure modes. These improvements contribute the remaining one-third of the Improved Diagnostics benefit.

The status of this prognostic capability varies among the engine subsystems. While certain gas path deterioration can be rather accurately trended, other engine malfunctions such as seals, bearings, and structural problems are still in a developmental status. Customer efforts to develop both the hardware, signal treatment, and criteria are currently receiving attention, and these efforts should be accelerated.

Troubleshooting and fault isolation capabilities are currently far superior to those in the baseline engines studied. Engine modularization and component accessibility are requirements in all new engines. Little additional emphasis appears necessary for the realization of the benefits shown.

It is important to realize, however, that improvements in prognostic capability must be accompanied by changes in the logistics system which will permit and encourage the ordering of components when the impending failure is first indicated. Without this capability in the logistics system, knowledge of an impending failure will have no real benefit. Despite this note of caution, the magnitude of the benefit indicated in this subgroup has been estimated without the assumption of any significant changes in the logistics system. Benefits from an improvement in the logistics system will be shown in subsequent discussions of other remedial action groups (Improved Logistics

Management Program).

The subgroup of Improved Ability To Consider Effects of Normal Operation is highly sensitive to the magnitude of the roller bearing skidding problem. As can be seen by comparing this subgroup on Figures 23 and 24, if severe roller skidding problems are assumed, the magnitude of improvement for this remedial action subgroup can be very large. A great deal of research has been directed at this problem. Studies and papers reporting progress are too numerous to mention. Recent experience on new engines experiencing roller skidding problems casts some doubt on the effectiveness of this research. Efforts to establish the actual state of the art in this technology require immediate attention.

On specific engine programs, a suspected lack of this technology can be offset through the incorporation of certain design approaches which would effectively preclude this problem. These actions are quantified and discussed in the remedial action group of Control of Design Configuration/Arrangement/ Materials.

The benefits in this subgroup also include an improved understanding of the effects of aircraft vibration upon engine reliability. This understanding includes both the ability to predict and/or specify the aircraft vibration environment as well as to predict how these vibration levels impose loads on the engine components. Efforts to understand and specify aircraft vibration levels have been initiated. Surveys of existing aircraft vibration levels and specification of limits for new designs have been implemented. It is believed that engine manufacturers currently possess the technology to utilize this information.

The subgroup of Improved Quality Control includes benefits from two specific actions as shown on Table LIV (Appendix II). Improved means of verifying adequate material properties of cast compressor wheels are the largest portion, with improvements in means of measuring nonmetallic compressor linings the remainder. On the particular display this compressor lining improvement is two-thirds of the total, which reflects the fact that only one engine possessed this failure mode in the engines examined.

Certain general conclusions appear appropriate for this remedial action group of Improved Technology. The development of hardware and analytical techniques relating to a relatively small number of failure modes achieves most of the benefits in this group. Customer actions to accelerate development in these areas can be extremely beneficial and highly cost effective. Much research has already been directed at these failure modes or components. Given the multitude of past efforts in these areas primary emphasis should be given at this point to obtaining a clear understanding of the current state of the art and an identification of future research required. Most of the benefits indicated in this group can be achieved on specific engine programs through careful design control and developmental testing. However, since improved technology in these areas would benefit nearly all turbine engines, the effectiveness of actions on specific engine programs should not dilute the necessity for aggressive customer attention in general research.

De-Emphasis on Performance/Weight

This remedial action group is divided into three subgroups which represent distinct areas of design concern. These three subgroups are:

Utilization of Axial/Centrifugal Over Axial Flow Compressors

This subgroup is self-explanatory. Although completely centrifugal compressors are currently in limited use and being proposed for future applications, it was not considered necessary to quantify the benefits of this design approach over completely axial flow compressors, due to the recognition that most of the benefits of a completely centrifugal design can be achieved with an axial/centrifugal design.

Specify Labyrinth Seals

This subgroup represents the design selection of a non-contacting seal that utilizes compressor bleed air for primary sealing functions.

Provide Adequate Low-Cycle Fatigue Life

Rather than a design selection as the previous two subgroups were, this subgroup is a requirement that is imposed upon the engine during early specification stages.

The common characteristic of each of these subgroups is that their benefits can be achieved only at the expense of some engine performance or weight: centrifugal compressors are generally recognized as not possessing the efficiency potential of axial compressors; use of labyrinth seals requires additional compressor bleed air (necessitating larger compressors to accommodate these losses); and higher low-cycle fatigue lives ultimately impact the weight of the engine.

These three subgroups contribute to the total De-Emphasis on Performance/Weight remedial action group as shown in Table XII, where the maximum benefit is shown for both the Composite and Particular engine baselines for both the Index Number and UER parameters. These values are shown in graphical form in Figure 25 for the Composite engine and in Figure 26 for the Particular engine.

TABLE XII. REMEDIAL ACTION SUBGROUPS FOR DE-EMPHASIS ON PERFORMANCE/WEIGHT

Remedial Actions	Maximum Benefit			
	Composite		Particular	
	Index	UER	Index	UER
Utilization of Axial/Centrifugal Over Axial Flow Compressors	6.08	.341	197.31	9.550
Specify Labyrinth Seals	3.19	.183	12.98	.750
Provide Adequate Low-Cycle Fatigue Life	.40	.001	.50	.001
Total	9.67	.525	210.79	10.301

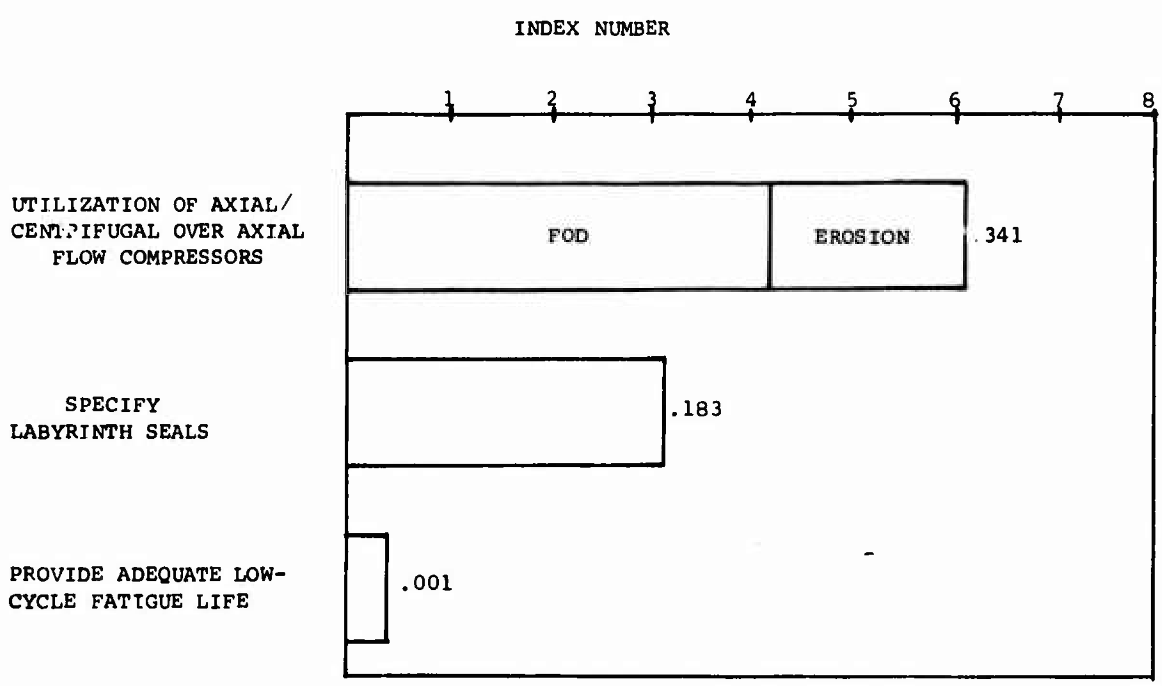

Figure 25. Remedial Action Subgroups for De-Emphasis on Performance/Weight for Composite Baseline.

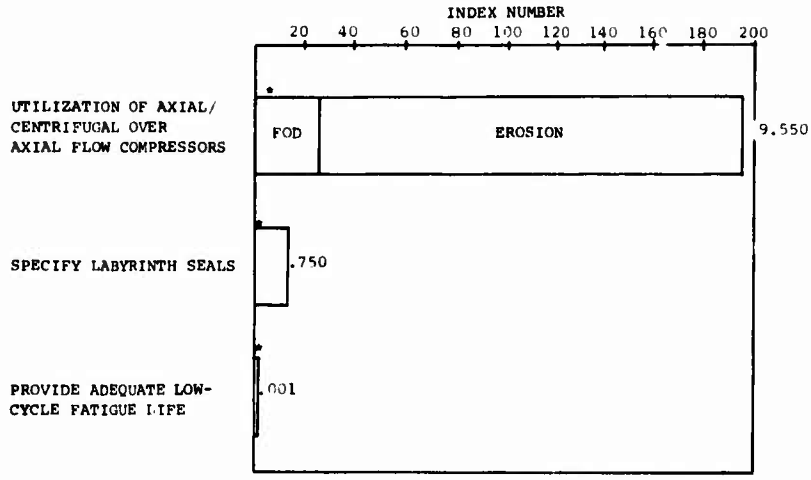

Figure 25. Remedial Action Subgroups for De-Emphasis on Performance/Weight for Particular Baseline.

In this remedial action group the effect of the engine baseline selection is very dramatic. The first two subgroups are very configuration sensitive, and the configurations of the engines in the Composite baseline obviously define the amount of benefit. Benefits shown against the Composite baseline in Figure 25 represent improvements that would be achieved on existing engines, where approximately one-half are axial/centrifugal designs, over two-thirds have some sort of inlet protection, and approximately one-half of the seals are already of a labyrinth type. With this background, the Particular engine display becomes more significant. The benefits shown for the Particular baselines (Figure 26) are maximum values which reflect, for example, that the benefit of an axial/centrifugal compressor over a complete axial flow compressor was calculated with both unprotected.

The Utilization of Axial/Centrifugal Compressor has a weight increase (for equal power) that has not been well quantified. The penalty, although real, cannot be significant when viewing the large number of engines of this configuration. Similarly, the relative vulnerability to erosion and FOD of these two configurations has not been, until recently, well defined. Frequently, failure mechanisms which define ingestion capability on specific engines have not been inherent to either the axial or centrifugal designs. Reference 1 reviews some of the literature relating to the relative ingestion capability of axial and centrifugal compressors. That a comprehensive review of past and predicted engine characteristics, relative to alternate compressor designs, should be performed was recommended in that report and is seconded at this time.

While this remedial action may certainly be evident during later preliminary design stages, it is imperative that any performance weight penalties imposed by such a design selection be acknowledged in the basic specification of engine requirements. Since the benefit of this remedial action is highly dependent upon other requirements such as inlet protection, the reader, who would require numerical quantification for his specific program application, is encouraged to review the detailed assumptions that contributed to these quantifications in Table XXII (Appendix I).

The subgroup of Specification of Labyrinth Seals is also a function of the configuration of Composite engine. As stated earlier, approximately one-half of the seals in the Composite engine were of a labyrinth type. The remaining one-half were carbon seals with circumferential-type faces. The quantification of the weight penalty of using labyrinth or similar type non-contacting seals is not well defined. The Reference 1 report cites studies which attempted to quantify this penalty but were inconclusive because of the procedures utilized (the assumption that the flow losses were unanticipated is not realistic). Certainly the large number of highly competitive engines that utilize partial or complete labyrinth seal configurations is evidence that the penalties are not excessive.

Given the observed reluctance in the engine design community to commit to this design approach and the desire to continue research on contacting seals, it is evident that the prime recommendation is that the weight/performance penalties of labyrinth seals be quantified under a range of engine sizes in order that conclusive trade-off decisions can be reached.

The last subgroup, Provide Adequate Low-Cycle Fatigue Life, is a benefit that appears inevitable. Recent model specifications have included requirements for low-cycle fatigue engine life of 15,000 cycles, which would certainly be adequate to achieve the benefits indicated. Since there does not appear to be any reluctance to include these requirements, further recommendations appear unnecessary.

The most obvious conclusion that emerges from this examination of the group of De-Emphasis on Performance/Weight is that there can be significant benefits from a few specific design decisions with some real but suspected exaggerated weight penalties. Incorporation of these design approaches is not a technology issue but a question of program emphasis. The role of the customer in this remedial action group is clear: priorities of objectives must be established and translated into design decisions.

Requirement for Specific Features

The remedial action group of Requirement for Specific Features has subgroups established which represent the two basic features whose installations are normally directly controlled by the customer. These two subgroups are:

Require Inlet Particle Separators

This subgroup is intended to represent the incorporation of inlet protection devices which prevent entrance of particles in the 1 to 100 micron size range into the compressor at efficiencies above 90 percent.

Require Inlet Protection Screens

This subgroup is designed to represent the benefit of installation of screens of a significantly greater mesh than the devices suggested above and whose primary function is the prevention of larger particles (debris) from entering the engine.

The contribution of these subgroups to the total Requirement for Specific Features is shown in Table XIII, where the maximum benefit is shown for both Composite and Particular engine baselines for both the Index Number and UER parameters. These values are shown in graphical form in Figure 27 for the Composite engine and in Figure 28 for the Particular engine.

TABLE XIII. REMEDIAL ACTION SUBGROUPS FOR REQUIREMENT FOR SPECIFIC FEATURES

	Maximum Benefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Require Inlet Particle Separators	2.72	.160	185.00	9.200
Require Engine Inlet Protection Screen	2.35	.138	34.59	2.00
Total	5.07	.298	219.59	11.200

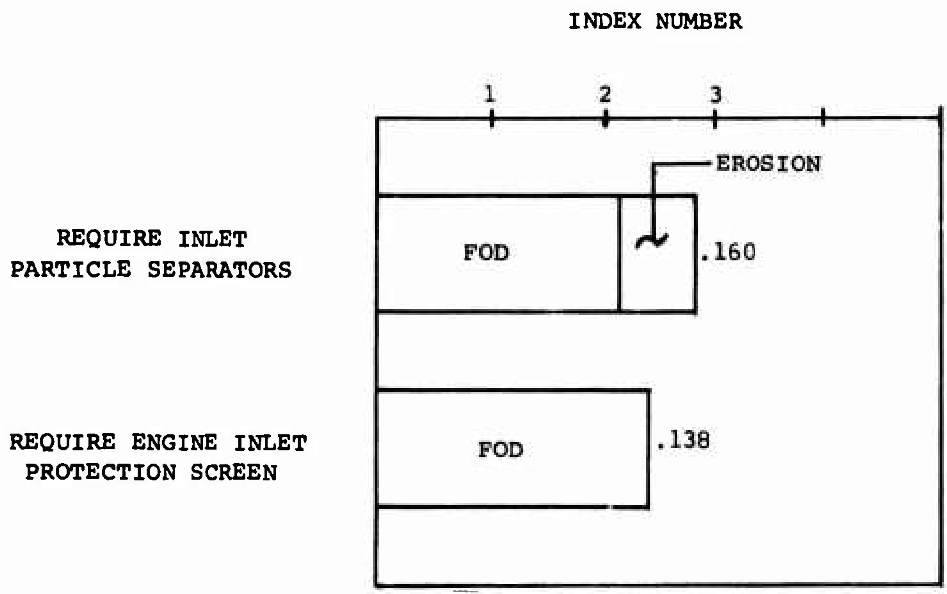

Figure 27. Remedial Action Subgroups for Requirement for Specific Features for Composite Baseline.

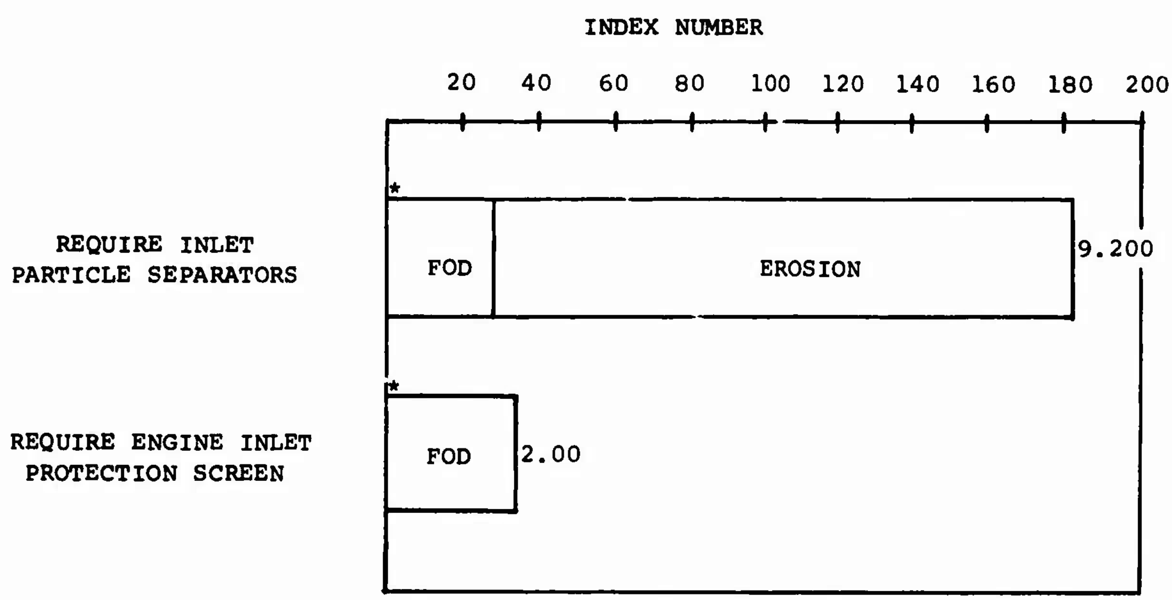

Figure 28. Remedial Action Subgroups for Requirement for Specific Features for Particular Baseline.

Both subgroups are dramatically affected by the engine baseline chosen against which remedial actions are quantified. This group, like the De-Emphasis on Performance/Weight group, is highly dependent on the engine configuration or installation. The benefit shown for the Particular baseline (Figure 28) for both subgroups (features) assumes that the feature has not been incorporated and that the engine configuration (all axial flow compressors) would produce the largest R&M problem and, therefore, the greatest benefit when these features are incorporated.

Since one-half or more of the engines in the Composite baseline have inlet protection devices (separators, filters, or screens) and have axial/centrifugal compressor designs, the benefits shown for the Composite engine are considerably less. To derive the benefit that would be appropriate for a specific engine, the reader should review the detailed assumptions and quantitative benefit shown on Table XXII (Appendix I).

The key characteristic of this remedial action group is that the incorporation of these features will be completely in response to customer requirements. These features appear to have been specified in the past independent of their performance, cost, or weight penalty. The motivation was usually an exposure to or anticipation of an environment which would require these features.

There are two technical issues that must be resolved before the incorporation of these features can be treated conclusively. The first issue is the capability of centrifugal particle separators to handle FOD. This issue must be understood in order to determine if screens are required in addition to these separators. Current research on third-generation separators directs substantial attention to this FOD question. FOD tests on new development engines can also determine if inlet screens are required. The second technical issue relates to screens and their ability to operate in icing conditions. There has been a reluctance to incorporate these screens where any possibility of icing conditions exists. The development of an all-weather inlet screen and an understanding of the cost and weight penalties associated with this capability should receive high priority.

Improved Maintenance

This remedial action group consists of three subgroups defined as:

General Improvement in Care and Skill

This subgroup reflects benefits that could be realized if the general attitude, morale and skill of maintenance personnel were improved. Calculations of benefits for this subgroup do not assume that this improvement is either feasible or practical. The inclusion of this subgroup is intended to suggest what might be realized if very radical changes in maintenance policies were contemplated. Benefits are included in this subgroup only when specific or individual actions would not be adequate.

Better Definition of Inspection Techniques and Repair and Troubleshooting Procedures

This subgroup represents the potential results if maintenance procedures were more thoroughly defined, transmitted, and utilized by the maintenance personnel. The characteristic that distinguishes this subgroup, as well as the next, from the previous subgroup is that specific actions could cause the benefits shown. The coverage of the many troubleshooting, repair, and inspection actions anticipated to be performed to a level of detail and clarity is the essential requirement in this subgroup.

More Complete Failure Criteria

This subgroup is the result of an improvement in the quality of definitions of failure. More an issue of depth rather than breadth, as required in the previous subgroup, these benefits could result if a better definition of allowable degradation was published and utilized.

These subgroups contribute to the remedial action group of Improved Maintenance as shown in tabular form in Table XIV and in graphical form in Figure 29. Both of these displays include both the Composite and Particular engine baselines.

TABLE XIV. REMEDIAL ACTION SUBGROUPS FOR IMPROVED MAINTENANCE

Remedial Actions	Maximum Benefit			
	Composite		Particular	
	Index	UER	Index	UER
General Improvement in Skill and Care	2.38	.161	2.38	.161
Better Definition of Inspection Techniques, etc.	1.30	.087	1.30	.087
More Complete Failure Criteria	.65	.044	.65	.044
Total	4.33	.292	4.33	.292

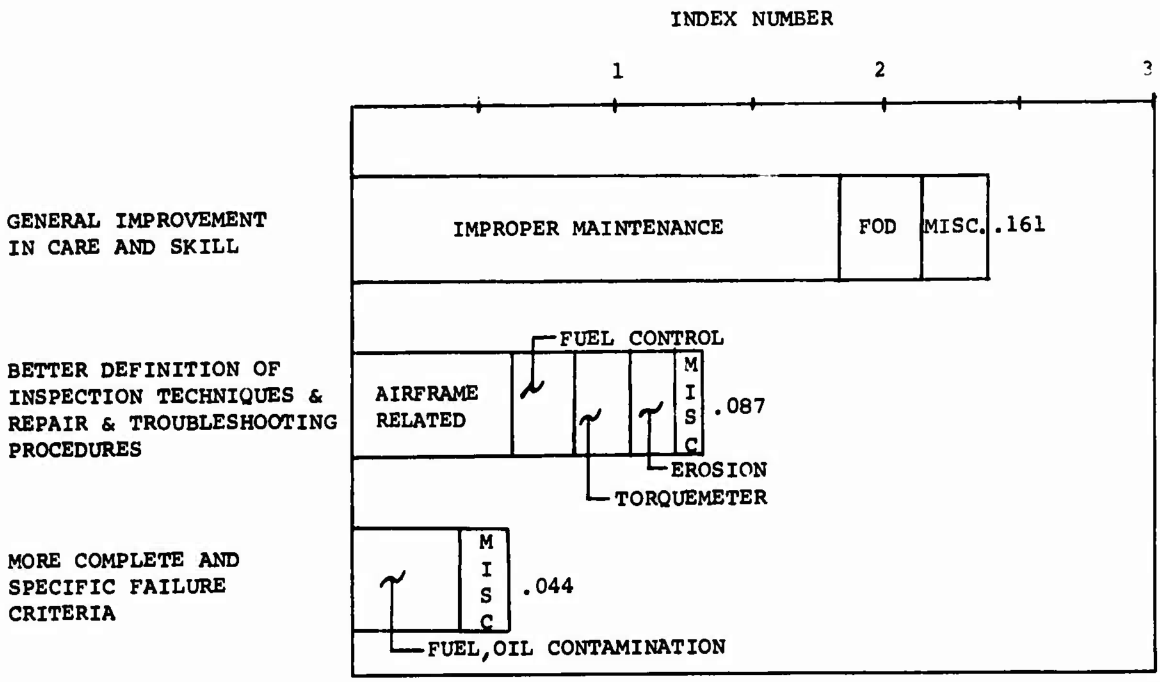

Figure 29. Remedial Action Subgroups for Improved Maintenance for Composite and Particular Baselines.

The subgroups shown are of two types: a general improvement activity that could affect all engines, and more specific actions that would be applied to each engine program.

The first subgroup, General Improvement in Care and Skill, contributes 55% of the total of these groups and primarily reflects the reduction of maintenance damage in the failure mode of Improper Maintenance. As suggested earlier, these benefits could be achieved only with an order-of-magnitude change in attitudes and skills of maintenance personnel. In Reference 1, the comparison of military and commercial maintenance damage rates was made conclusively. Despite a variety of environments, services, and engine configurations, the pattern of military maintenance damage rates five to ten times greater than the commercial experience was observed.

The fundamental reason for this difference is not clear to the authors. Little practical research has been directed at this subject. A wide variety of recommendations appear in order. Certainly top-level studies by human factors engineers in cooperation with experienced maintenance personnel that would attempt to define the specific factors that contribute to this situation could be beneficial. At the other extreme, perhaps a "rotation" of military and commercial maintenance personnel might provide on-the-spot suggestions that provide clues for the ultimate solutions.

Given the large potential for improvement in this area, further work certainly seems appropriate. With the problem well recognized, it only remains for the engineering (design) and maintenance management agencies to agree on future courses of action.

The next subgroup, Better Definition of Inspection Techniques and Repair and Troubleshooting Procedures, are benefits much more easily attained than the previous subgroup. Removals of engines from airframes due to problems in adjacent or separately removable components reflect, to a significant extent, a lack of adequate understanding of the unique characteristics of each engine installation. A variety of failure modes could benefit from an improvement in this understanding. As shown on Figure 29, airframe-related removals which arise when problems on airframe components result in engine removals are usually unnecessary. Similarly, it is rare that a fuel control failure necessitates an engine removal. The torquemeter portion represents more the actual damage that has occurred when engine

modules are assembled onto the engine in an inadequate fashion. The erosion failure mode portion reflects those removals where inadequate troubleshooting procedures were utilized.

While the realization of these benefits must begin with the preparation of the maintenance manuals in a more complete manner, it must continue into the training and support activities. The manuals must be kept current with changes and must be readily available for constant use. A frequent complaint is that existing manuals are too bulky and generally inaccessible. This situation must be remedied if the benefits of this subgroup are to be achieved.

The More Complete and Specific Failure Criteria subgroup requires extensive continuing engineering support to assist in the clear and practical definitions of failure criteria. Fuel and oil contamination could benefit significantly from this effort. Currently, engine manufacturers do not participate sufficiently in the determination of allowable lubrication contamination levels. These criteria have been established by the military agencies, frequently without the benefit of good data (teardown information) feedback. The use of SOAP (Spectrographic Oil Analysis Program) to determine failures of oil-wetted components has grown, but the technical base upon which its removal criteria are determined has been exceeded by the desire to implement the system. This has produced unnecessary removals.

Fuel contamination is not used as an indication of failure but is a matter of concern because of the effect on fuel system components such as fuel controls, control valves and nozzles. Here perhaps more stringent criteria are appropriate.

In the cases of both oil and fuel contamination, general information can be of value, but ultimately much that is unique to each engine installation becomes the dominant issue. This should be addressed during the development list program and early service experience and specific failure criteria established.

There are two perspectives that could be adopted on the basis of the benefits shown for each subgroup. One, of optimism, would view the large contribution (55%) of the General Improvement subgroup as a real potential for R&M improvement without the necessity of specific actions on each engine maintenance program. That view would see the advantage of a general improvement affecting many (perhaps all) engine programs.

The other view, more pessimistic and shared by the authors, sees the great difficulty in changing the overall maintenance environment and recognizes that, practically speaking, only on a specific program can improvements be generated. The benefits of these actions are embodied in the last two subgroups which could provide relief to only 45% of the total possible.

The high ranking (5th) of this remedial action group should encourage continued research. The benefits are too great to accept the maintenance situation as inevitable.

Control of Design Configuration/Arrangement/Materials

This remedial action group consists of specific design decisions that could be strongly influenced by the customer. The design selections in this group are unlike the design choices in the group of De-emphasis on Performance/Weight, in that performance/weight penalties are not significant restraints to the incorporation of the design options cited here. They are unlike the design issues in the Emphasis on R&M in Requirements, in that they are sufficiently visible to be readily controlled directly by customer dictates.

The design options used here as subgroups are generally self-explanatory and do not require definition.

The contribution of the most significant of these design options to this remedial action group is shown in Table XV in tabular form for both the Composite and Particular engines and in graphical form in Figure 30 for the Composite engine and in Figure 31 for the Particular engine.

TABLE XV. REMEDIAL ACTION SUBGROUPS FOR DESIGN CONFIGURATION/ARRANGEMENT/MATERIALS

	Maximum Benefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Require Electrical Torquemeter	1.13	.043	5.83	.222
Specify Bearing Positive Retention	.61	.032	3.10	.150
Preclude Use of Rear-Drive Engine	.39	.015	3.38	.520
Use Most Corrosion-Resistant Materials	.31	.028	.66	.006
Use Elliptical Outer Race Bearings	.30	.013	2.10	.010
Miscellaneous	1.01	.033	4.36	.133
Total	3.75	.164	19.43	1.041

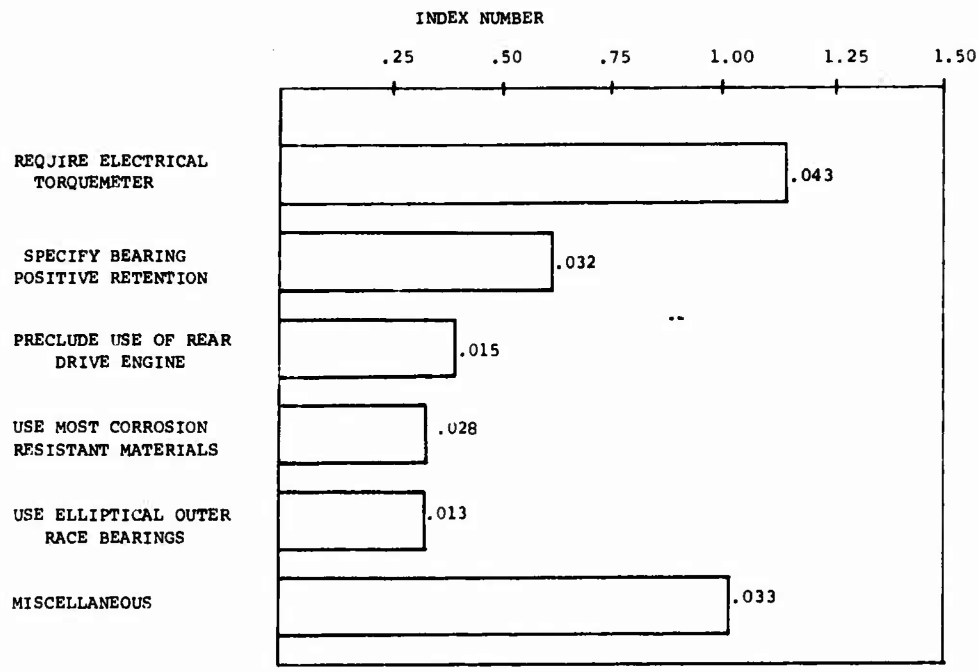

Figure 30. Remedial Action Subgroups for Control of Design Configuration/Arrangement/Materials for Composite Baseline.

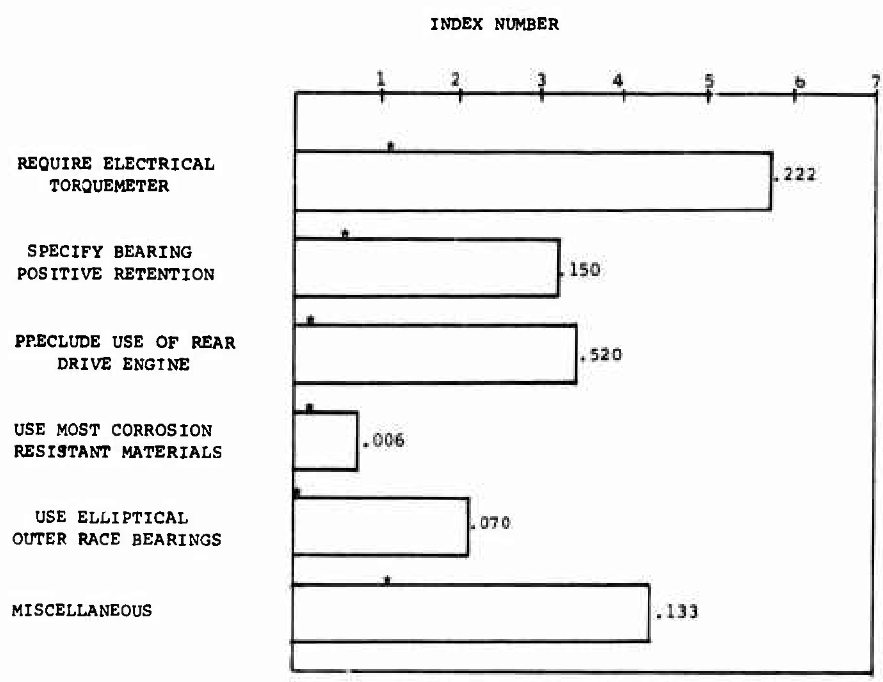

Figure 31. Remedial Action Subgroups for Control of Design Configuration/Arrangement/Materials for Particular Baseline.

The ranking of the benefits of these options does not vary significantly from the Composite to the Particular baselines. Each of these desirable design options has been omitted and created excessive R&M problems on one or more of the engines studied. The Particular values, therefore, are all generally four to seven times the Composite values.

The subgroup of Require Electrical Torquemeter could just as well be termed Avoid High-Speed Mechanical Torquemeter since the entire benefit shown represents the avoidance of the R&M problem with one engine with the only high-speed mechanical system. On engines with reduction gearboxes (low speed output), hydromechanical designs are utilized with excellent reliability: it is only on a high-speed output engine that a mechanical system was adopted with resultant removal rates over fifty times as great as the hydromechanical systems (see data in Reference 1).

The achievement of this benefit will, most likely, be achieved without effort. Electrical designs have emerged from several manufacturers. Reference 5 documents research on one such system. Further customer action does not appear necessary.

The design feature of Specify Bearing Positive Retention relates primarily to outer race retention policy. The repetitiveness of outer race rotation (spinning) problems and the lack of real progress in developing predictive methods would suggest that positive retention should be readily accepted as standard practice. Unfortunately, for reasons detailed in Reference 1, this is not the case, and customer actions will be required to assure that these benefits are realized.

The subgroup entitled Preclude Use of Rear Drive Engines is unlike the other subgroups in that the type of engine output is not an option normally exercised by the manufacturer. The ultimate airframe installation dictates this design. All recent engines are of a front drive configuration, and this subgroup may be a somewhat academic issue.

---

[5] Scoppe, Frank E., ADVANCED TORQUE MEASUREMENT SYSTEMS TECHNIQUE FOR AIRCRAFT TURBOSHAFT ENGINES, Avco Lycoming Division, USAAMRDL Technical Report 73-37, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, June 1973, AD771965.

The Use of Most Corrosion Resistant Materials is a benefit that will require the most careful control by the customer. The best materials for the application are frequently a matter of debate even among metallurgists. What must be avoided is that corrosion resistance is compromised for strength. Strength can be obtained with bulk; chemical characteristics are inherent to the material.

The Use of Elliptical Outer Race Bearings addresses the problem of roller bearing skidding and represents the benefit if elliptical outer races were used to prevent this common failure mode. This approach is the usual resolution to a test or service revealed problem, but it is rarely utilized during the initial design. The reasons for this reluctance have been itemized in Reference 1.

Despite this reluctance, the customer should specify this feature until such time as the technology is achieved to assure that the roller skidding problem is completely understood and controllable. The recommendation that this technology be summarized was offered previously in the discussion of the Improved Technology remedial action group.

Each of these subgroups or design options is capable of direct control by the customer. This control could be exercised in several ways. First, the basic specification (RFP) for a new engine could specify these design approaches. While undoubtedly restrictive to the engine manufacturers, this approach has been adopted for one of these subgroups (positive retention of bearing outer races) on a recent new engine RFP.

Another approach is to specify aggressive R&M goals and require such definitive justification for achievement potential that the incorporation of these designs would be inevitable.

A third approach is simply to select from among the competing engines the one that incorporates most of these features. The difficulty of this approach is twofold: first, if R&M is not clearly stated as a prime objective, it is unlikely that any engine would incorporate all of these features; secondly, even if one engine did possess all of these features, other objectives could cause it not to be selected.

The last approach is that the customer would exercise a design authority during the preliminary design stage. The contractual arrangements must be structured to permit this interface.

Each approach is feasible, and each has its advantages and disadvantages. The real restraint has been and will be, not a lack of procedures or methods, but a commitment on the part of the customer to improved R&M.

Increased Use of Analytical Procedures

This remedial action group consists of three subgroups which describe the types of analytical procedures used to calculate the benefits in this remedial action group. The three subgroups are:

Implementation of Improved Design Practices

This subgroup represents the benefits of additional efforts during the design stage to implement practices which are clearly superior from an R&M standpoint and require little, if any, sophisticated analysis. On the continuum from analysis to practices, the improvements in this subgroup encompass the practices end. Although these practices are basically analytical procedures, their lack of complexity warrants separation from the remaining subgroups.

Consideration of Abnormal Conditions

This subgroup represents benefits that could be realized if additional emphasis were applied to routine analysis to encompass greater considerations of potential abnormal or unusual conditions. These conditions could relate to the manufacturing of the engine, the environment (climatic, maintenance and operating), or the consequences of other engine failures.

Consideration of Normal Conditions

This subgroup is similar to the previous subgroup but includes the benefits from additional consideration of the normal operating conditions.

These subgroups contribute to the group of Increased Use of Analytical Procedures as shown in tabular form in Table XVI for both the Particular and Composite baselines, and in graphical form in Figure 32 for the Composite baseline and in Figure 33 for the Particular engine.

TABLE XVI. REMEDIAL ACTION SUBGROUPS FOR ANALYTICAL PROCEDURES				
	Maximum Lenefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Implementation of Improved Design Practices	1.45	.072	5.49	.297
Consideration of Abnormal Conditions	1.23	.046	13.58	.603
Consideration of Normal Conditions	.48	.027	4.71	.119
Total	3.16	.145	23.78	1.019

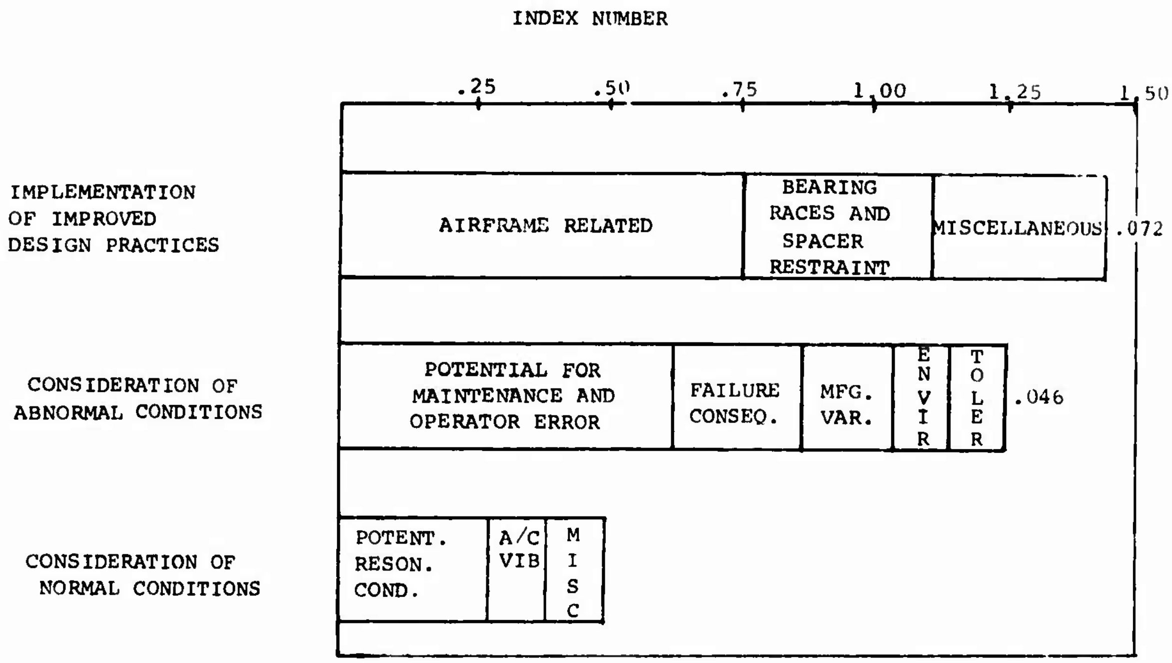

Figure 32. Remedial Action Subgroups for Analytical Procedures for Composite Baseline.

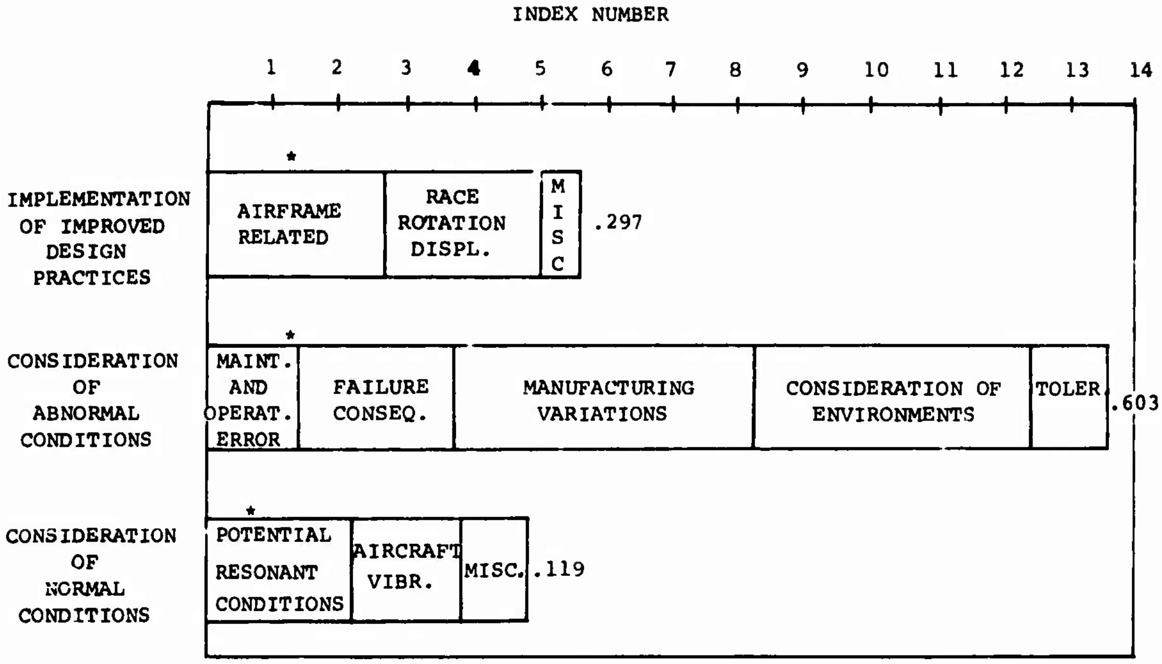

Figure 33. Remedial Action Subgroups for Analytical Procedures for Particular Baseline.

The relative contribution of the three subgroups varies dramatically between the Composite prioritization (Figure 32) and the Particular prioritization (Figure 33).

The subgroup of Consideration of Abnormal Conditions becomes the dominant benefit against the Particular baseline with over twice the benefit of the other two subgroups. Th. large benefit is due to the large R&M problems that have occurred on various specific engines due to conditions that can best be termed abnormal. As shown in Figure 33, there are five basic types of abnormal conditions: maintenance and operator errors, consequences of failures, manufacturing variations, environmental conditions, and tolerance buildups. Without debating whether these situations should be called abnormal or not, suffice it to say that they have frequently been overlooked or disregarded during the routine analysis that supports an engine design.

By comparing Figure 32 and Figure 33, it can be seen that manufacturing variations and environment issues are the major factors in increasing the benefits of this subgroup in the Particular baseline.

The Implementation of Improved Design Practices has a relatively high benefit in the Composite display and consists primarily of improvements in airframe-related removals and problems with bearing races. These improvements could be achieved through adherence to design practices generally recognized as benefiting R&M. Specifically, for the two problems mentioned, assurance that the minimum number of failure modes cause engine removals and the use of positive retention on bearing races are the prime efforts required. The former of these is an activity that must be performed more by the airframe than the engine manufacturer.

The Consideration of Normal Conditions subgroup is driven primarily by an increase in the application of analysis directed at potential resonant conditions. This activity could uncover the frequent problems, usually in the compressor section, that cause engine damage, severe power losses, and occasionally accidents. The other prime source of benefit is a greater consideration of the anticipated aircraft vibration environment.

Overall, this remedial action group has the potential for addressing a variety of failure modes, many of which are difficult, if not impossible, to resolve after the design has been committed to production. This entire group is merely the more thorough application of analysis procedures that are normally performed routinely at some level of execution.

Despite the fact that these efforts would be an extension of existing efforts and would not, except in a few cases, produce significantly different designs, the cost of this remedial action group will not be insignificant. The analysis included in this group is viewed as being cost-effective; however, it will require funds and time to implement on each engine program.

The priority for implementing this group should be evaluated by examining the failure modes that are addressed by this remedial action group as opposed to other groups. Only the Testing group has the potential for resolving many of these modes. Since the testing activity occurs at a rather late point in the development process, these analytical approaches should appear attractive.

Decrease in Functional Requirements

This remedial action group consists of benefits where specific functional requirements are not imposed on the engine design. The main characteristic of this group is that the functional requirements included are not essential to the engine and are incorporated only when indicated by the customer. In a sense this group is similar to the remedial action group of Requirement of Specific Features. In that group, features that improved R&M but did not increase any functional capability were addressed. In both groups, customer dictates are the determining factor.

Two subgroups are established which represent the two basic design characteristics under consideration. These two subgroups are:

Elimination of Power Management System

This subgroup is the benefit if a complete power management system was not required. Power management systems, which are designed primarily to reduce pilot workload, add a dimension of complexity to the fuel and electrical systems with their attendent R&M problems.

Elimination of High-Speed Output

This subgroup does not affect the actual function of the engine but has been included in this group because engine output speed is clearly a customer specified requirement.

The contribution of these subgroups to the total Decrease in Functional Requirements remedial action group is shown in Table XVII, where the maximum benefit is shown for both Composite and Particular engine baselines for both the Index Number and UER parameters. These values are shown in graphical form in Figure 34 for the Composite engine and in Figure 35 for the Particular engine.

TABLE XVII. REMEDIAL ACTION SUBGROUPS FOR DECREASE IN FUNCTIONAL REQUIREMENTS				
	Maximum Benefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Elimination of Power Management System	1.48	.032	9.70	.210
Eliminate High-Speed Output	1.14	.043	5.91	.225
Total	2.62	.075	15.61	.435

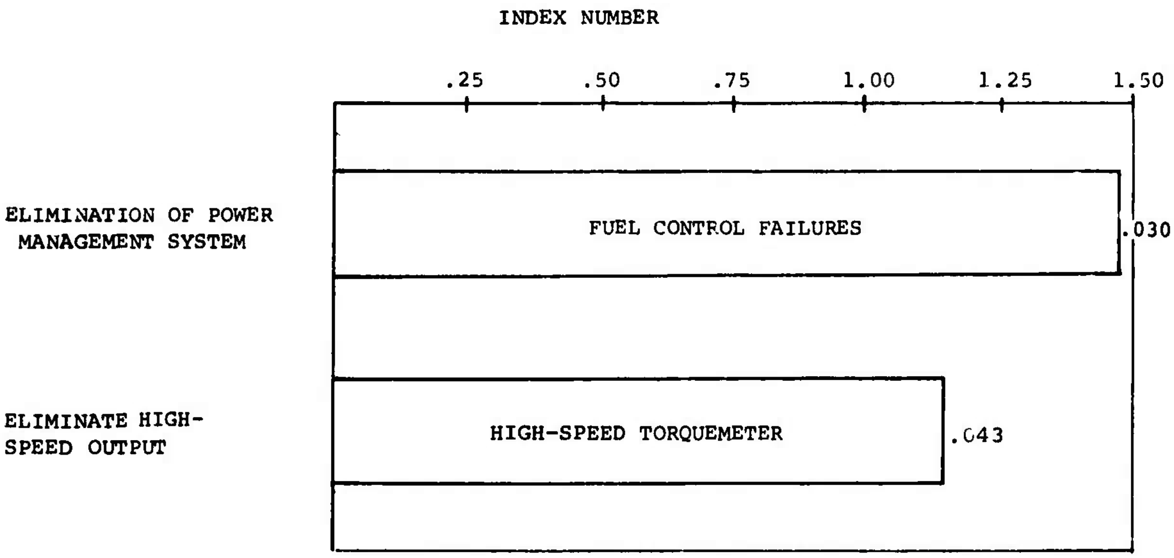

Figure 34. Remedial Action Subgroups for Decrease in Functional Requirements for Composite Baseline.

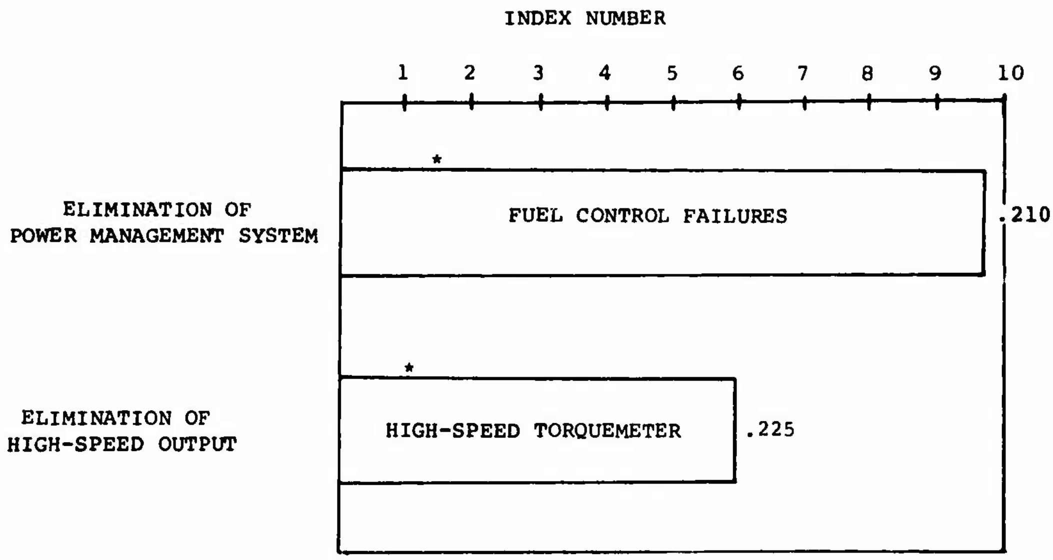

Figure 35. Remedial Action Subgroups for Decrease in Functional Requirements for Particular Baseline.

Both subgroups increase their benefits significantly in the Particular baseline, because the impact on engine R&M due to these features was manifested on only one engine for each feature in the engines studied.

The benefit of the Elimination of Power Management Systems is realized in the reduction of fuel control problems. The benefit shown for fuel control is not only actual failures that were due to the additional complexity but erroneous removals due to inadequate troubleshooting of the complete system. Inadequate troubleshooting appears to be the natural result when a highly complex system is installed that is difficult to troubleshoot. The benefit of this subgroup may be distorted because of the poor accessibility of the fuel control on the one aircraft which possessed this power management system. This poor accessibility led to frequent engine removals. When problems were encountered on an engine installation with better accessibility, the magnitude of the problem, and therefore this benefit, were not as great. Anticipated improvements in engine accessibility in future engines would, therefore, minimize the benefit of this remedial action subgroup. Also, improved design approaches to power management systems would achieve R&M benefits similar

perhaps to those shown when the entire function was eliminated.

The elimination of high-speed output causes a benefit in the torquemeter system. As discussed previously in the remedial action group of Control of Design Configuration/Arrangement/Material, the dual requirement of a high-speed output and a torquemeter integral to the engine were coupled in only one engine and produced a mechanical torquemeter system with extremely poor R&M characteristics. The benefits shown could be achieved either through elimination of the high-speed output requirement or by the control of the design approach to be an electrical type system. The former approach is included in this subgroup; the latter approach, in the remedial action group of Control of Design Configuration/Arrangement/Materials. Both approaches would produce similar R&M benefits.

This discussion of these two subgroups indicates that the benefits of this entire remedial action group may be [illegible] inflated. Alternate remedial actions, in terms of design approaches, will most likely achieve the benefits shown in spite of a continued requirement for these functional requirements. The conclusion seems apparent that the customer need not be concerned about the R&M impact of the functional requirements imposed on future engines.

Improved Logistics Management Program

No subgroups are established for this remedial action group. It is established to indicate the potential benefits if spare engines were more readily available and fewer engines were removed for cannibalization. The entire benefit for this group is in the Convenience subsystem. Convenience removals, as shown in Reference 1, are a function of both the basic removal rate of the engine and the particular logistics situation. While the general trend is higher rates of convenience removals with increasing total removal rate, there are interesting exceptions to this pattern. Engine models which enjoy adequate spares availability experience lower convenience removal rates. It would be shortsighted, however, to simply recommend that greater quantities of spare engines be made available. That recommendation would produce higher cost that would not, perhaps, be offset by the increased aircraft availability and reduced maintenance that would result. What is needed is an improvement in the spares program. There are, in the authors' view, two aspects to this management. The first is the consideration of the availability of spares as a function of the engine development and service schedule. Specifically, the inevitable reliability growth that occurs must be considered because of the dual effects of decreasing removal rates and the changing configuration of the engine. The dilemma here that must be resolved is whether to buy large quantities of pipeline spares early in the program to maintain high availability at a point where the reliability is poor and suffer the consequences as these spares become of an outdated configuration; or to defer the procurement of spares to a point where the configuration and reliability have somewhat stabilized and suffer the consequences of the early unavailability of adequate spares. Clearly there is no single answer to this dilemma but only the best compromise which produces a logistics situation that meets minimum operational requirements at a reasonable cost.

The second dimension to the logistics management program is not a question of the number or delivery timing of spares but rather their optimum location. This includes the availability of spares at the proper geographical location and maintenance level that produces maximum aircraft availability.

The entire issue of logistics management is too complex to be adequately addressed in this report. However, two trends should be recognized as contributing to the potential benefits

indicated. The first trend is the growing recognition that a significant value of a development test program can be an improved understanding of the reliability characteristics of an engine. Reference 3, in discussing the value of endurance testing for engines, recognized that there are additional benefits to the development test program over and above its ability to detect problems, allow solutions and improve reliability. The report noted:

> "A second point, which is frequently overlooked is that the results of endurance testing is the best information available to serve as a basis for the establishment of the initial engine overhaul removal interval (flying hours/removals). This is the value that determines how many spare engines we must buy and how much must be spent on initial spare parts. The more accurate the initial overhaul removal interval is, the more effectively support funds can be allocated."

The second major trend is the increased analytical capabilities developing that could be applied to the optimum spares procurement program. Two analytical techniques are of specific value. The first is the emerging capability to predict reliability growth as a function of the desion and program characteristics of a particular engine program. This methodology could allow a better understanding of what reliability levels will or could be achieved at various points in the development and operational cycle. The second trend is the development of simulation models which can project maintenance and logistics requirements through the reproduction of the reliability, operational, maintenance, and logistics situation. These simulation models, when coupled with reliability growth predictions, could allow an optimization of spares requirements.

In spite of these capabilities, it does not appear that the individuals responsible for logistics management have adequately recognized the value of these methods. A responsibility clearly exists for the engineering community that has developed these methods to interface with the logistics organizations to insure maximum utilization. Recognition must be made of the fact that frequently spares procurements are dominated by concerns that are difficult to define, let alone quantify. Historically, weapons systems, and particularly spares, are procured in the military environment with the concept that a capability must be maintained independent of the current operational situation.

These reserve capability requirements have usually dominated the procurement policies, and analytical methods that would attempt to determine spares requirements must acknowledge these requirements and not be limited to static operational situations.

The need for improved logistics management is well recognized and requires no additional impetus from this analysis. It is a common problem among the various military services and is well recognized as requiring priority attention. What is required is the recognition that the engineering (design and reliability) community could provide assistance to the resolution of the problem. Because of organizational structures in both the military and contractor houses, this cooperation has been minimal in the past. These organizational obstacles must be overcome and aggressive programs adopted that would integrate the skills of both communities.

General Emphasis on R&M in Requirements

This remedial action group represents those benefits that could be achieved as higher requirements are imposed for R&M in the specification of engines. It includes the results of those actions taken by the engine manufacturer that are performed in direct response to aggressive R&M requirements and that would (will) not be performed otherwise. The differences between this remedial action group and the Increased Use of Analytical Procedures is that this group will produce rather obvious differences in the design. The activities included in the Increased Use of Analytical Procedures are basically the more thorough application of analytical methods that are routinely performed and would not result in obvious design differences.

The difference between this remedial action group and the group of Control of Design Configuration/Arrangement/Materials is that this remedial action group would require the emphasis on R&M. The design features in the Control of Design Configuration/Arrangement/Materials are of such detailed and visible nature that control by the customer could be exercised independent of R&M emphasis and at many stages of the early development process. This group of General Emphasis on R&M encompasses those design approaches which must be chosen at the very earliest stages of engine development and can only be fully implemented in an atmosphere where there is a clear concensus that R&M is of high priority. This group consists of five subgroups, which are:

Additional Consideration of Maintenance Durability

This subgroup describes the benefits if the design acknowledged the actual maintenance environment to which the engine would be ultimately subjected. Implicit in this benefit is a level of effort far exceeding that which is currently applied to engine design. Dramatic and innovative design approaches are envisioned as the necessary prerequisite to this achievement.

Additional Consideration of Helicopter Environment

The vibration environment of the helicopter is the prime factor in this subgroup. Benefits are calculated where recognition of the eventual helicopter vibratory loads is given high priority.

Greater Consideration of Operation on Engine/Aircraft

Similar to the first subgroup which acknowledged the maintenance environment, this subgroup describes benefits if all of the potential abuses due to operator technique and criteria were considered.

Require Higher Lives on Gearbox Bearings and Seals

This subgroup describes the effect of greater R&M emphasis in the design of the many small bearings and external seals in the accessory sections of the engine. Included in this subgroup are all bearings and seals which are not utilized for main spool support or for specific functions such as torquemeter. Bearings utilized in the power reduction train are included.

Require Higher Lives on Main Shaft Bearing

This subgroup is reserved for the benefit potential when greater life is required in the bearings supporting the primary spools.

These subgroups contribute to the emphasis on R&M in requirements as shown on Table XVIII, where the maximum benefit is shown for both the Composite and Particular engine baselines for both Index Number and UER parameters. These values are shown in graphical form in Figure 36 for the Composite engine and in Figure 37 for the Particular engine.

TABLE XVIII. REMEDIAL ACTION SUBGROUPS FOR GENERAL EMPHASIS ON R&M IN REQUIREMENTS

	Maximum Benefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Additional Consideration of Maintenance Durability	.85	.050	2.55	.150
Additional Consideration of Helicopter Environment	.39	.009	1.80	.053
Greater Consideration of Operation on Engine/Aircraft	.25	.012	.42	.020
Require Higher Lives on Gearbox Bearings and Seals	.20	.004	.39	.007
Require Higher Lives on Main Shaft Bearings	.18	.003	1.40	.025
Total	1.87	.078	6.56	.255

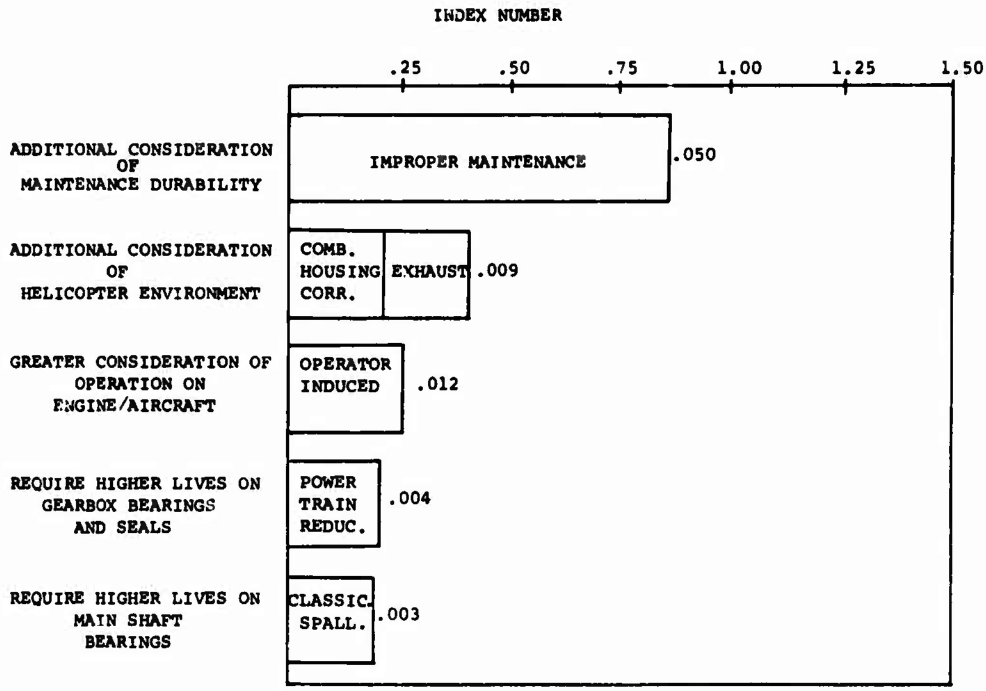

Figure 36. Remedial Action Subgroups for a General Emphasis on R&M in Requirements for Composite Baseline.

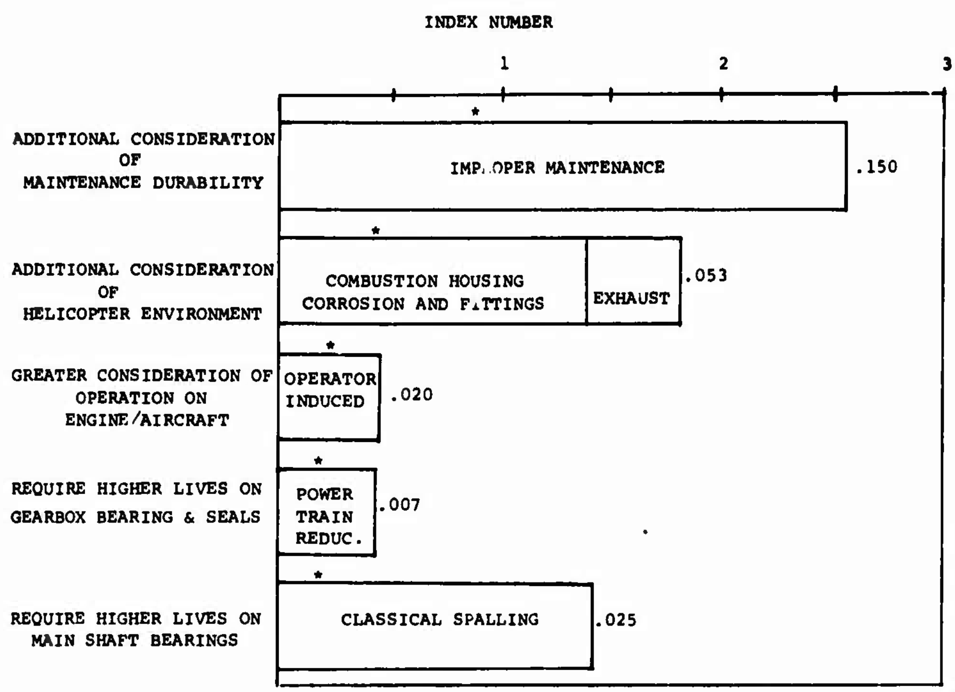

Figure 37. Remedial Action Subgroups for a General Emphasis on R&M in Requirements for Particular Baseline.

It is interesting that there is not a significant increase in the magnitude of benefits from the Composite to the Particular baseline for most of these subgroups. This is because the problems which these remedial actions address are generally inherent to all of the engines examined, and no single engine contributed to an unusually high portion to the Composite values. The only significant ranking difference between the Composite and Particular engine baselines is the increase in importance of the main shaft bearing subgroup against the Particular baseline. This is due to the fact that only one engine of those examined had any considerable failure rate due to classical fatigue spalling which could be related to a basic sizing issue. Usually other bearing failure modes dominate the classical spalling mode, and it is only when extremely low lives are present that the classical spalling mode is of any significance.

The other subgroups are generally self-explanatory and require little discussion. Each of the subgroups will require dramatic actions for achievement. Restraint to incorporation has not and will not be a performance or weight emphasis but rather a lack of sufficient priority for R&M that these extraordinary activities would not be considered. Realization of the benefits of this subgroup will require both strong customer R&M emphasis as well as creative and dedicated responses by the engine manufacturers.

Provide Greater Flexibility in Scheduling

Subgroups for this remedial action group were not established since only two failure modes appeared to have been caused by an emphasis on compressed scheduling. As shown in Figure 8, the only failure modes related to this characteristic were compressor blade/disc fatigue failures and turbine nozzle band cracking. Benefits shown in Table IX are due to approximately equal contributions from these two failure modes.

The manner in which an emphasis on scheduling affected these failure modes requires examination. While several engines contributed to the failure mode of compressor blade/disc fatigue failures, only one engine was sensitive to the scheduling issue. In that particular case, at issue was the incorporation of a new compressor disc configuration on a growth model of the engine. Airframe and other schedule commitments prevented the required new configuration from being incorporated. In the case of turbine nozzle band cracking, the schedule impact here is more universal and appears to have affected all engines. A more reliable alternative to fabricated nozzle assemblies is integrally cast nozzles. These, however, require greater time for tooling and restrict the flexibility in changing vane shapes or configurations. This restraint, however, would appear to be dissolving if current new production engines are an indication. On these engines, integrally cast nozzles are being incorporated at the initial design, apparently in spite of the effects on the scheduling.

Because of different reasons, the benefits of this remedial action group appear to be achievable without much additional customer action. Despite this apparent lack of immediate future attention, the indirect benefits of Greater Flexibility in Scheduling should not be forgotten. Other remedial actions, for example, Test and Increased Use of Analytical Procedures, do require consideration in establishing development schedules. However, the direct imposition of those remedial actions should result in the identification of the schedule impact, and relief in schedules need not be viewed as a prime contribution to future R&M improvements.

Additional Control of Engine/Airframe Interface

This remedial action group describes the benefits if the relationships between the engine and airframe manufacturers were formalized and executed with more thoroughness. Four subgroups are established:

- Insure Access to All Components
- Specify Close Location of Screen
- Specify Pod-Mounted Engines
- Provide Adequate Control Protection Devices

These subgroups are generally self-explanatory and do not require further definition. They contribute to the total remedial action group as shown in Table XIX for both the Particular and Composite baselines, where the maximum benefit is shown in tabular form for the Index Number and UER parameters. In graphical form the benefits are shown in Figure 38 for the Composite engine baseline and in Figure 39 for the Particular engine baseline.

TABLE XIX. REMEDIAL ACTION SUBGROUPS FOR ADDITIONAL CONTROL OF ENGINE/AIRFRAME INTERFACE

	Maximum Benefit			
	Composite		Particular	
Remedial Actions	Index	UER	Index	UER
Insure Access to All Components	.73	.026	6.66	.177
Specify Close Location of Screen	.20	.013	.14	.008
Specify Pod-Mounted Engines	.15	.007	20.71	1.000
Provide Adequate Control Protection Devices	.12	.006	1.20	.060
Total	1.20	.052	28.71	1.245

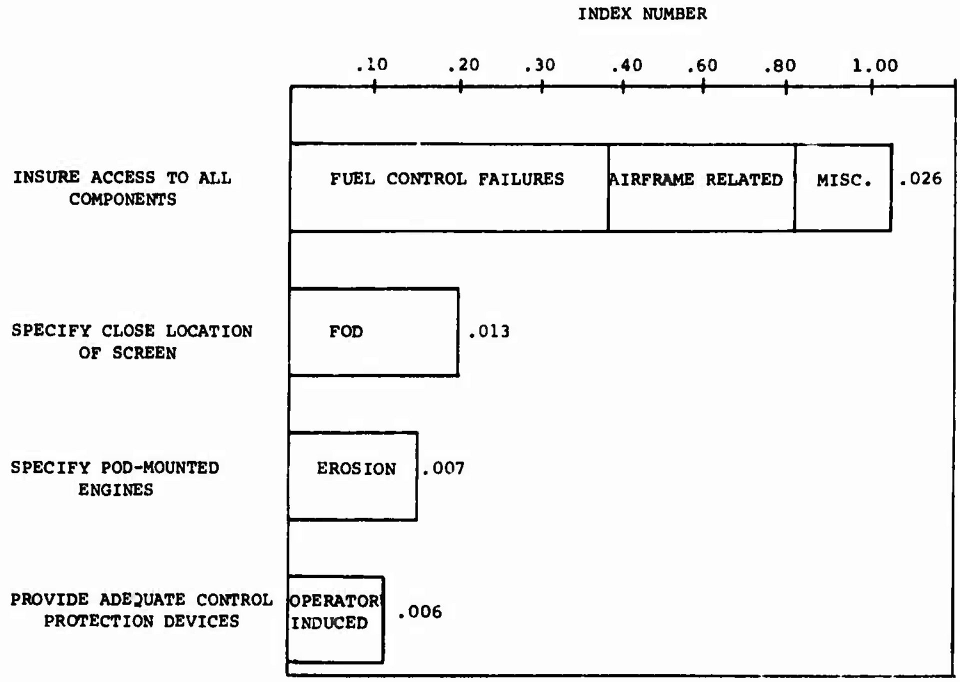

Figure 38. Remedial Action Subgroups for Additional Control of Engine/Airframe Interface for Composite Baseline.

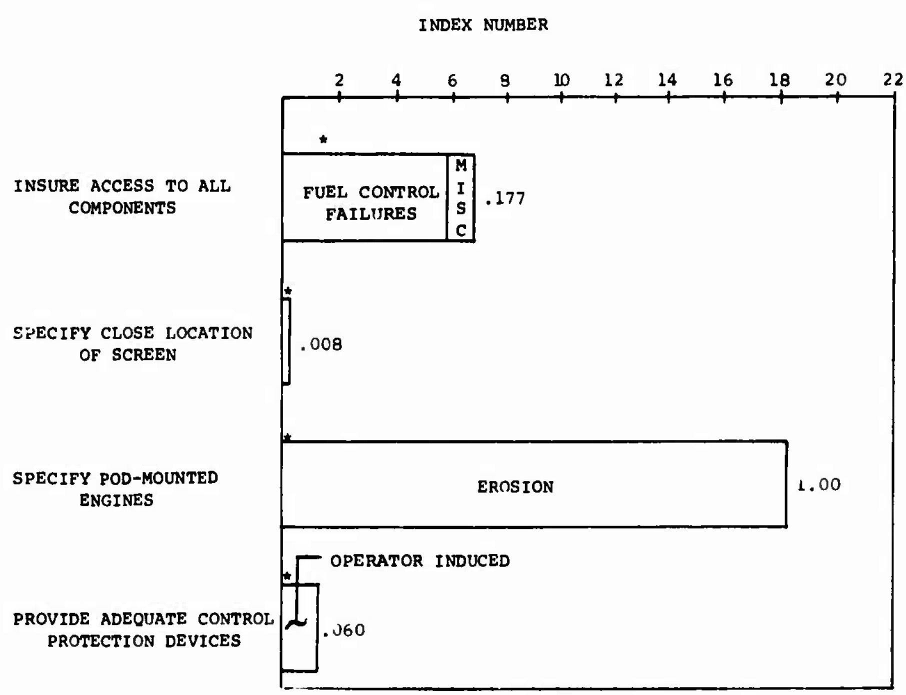

Figure 39. Remedial Action Subgroups for Additional Control of Engine/Airframe Interface for Particular Baseline.

Comparing the Composite to the Particular baseline displays reveals several significant issues. The impact of two failure modes changes the rank ordering of the subgroups and greatly increase the absolute benefit for the entire remedial action group.

The highest ranking subgroup in the Composite display, Insure Access to All Components, is driven by two failure modes: fuel control failures and airframe-related engine removals. Of these two modes, the fuel control is more important in terms of its potential, on an individual engine, to be approximately ten times as great as the airframe-related mode.

Insuring adequate accessibility requires more than good intentions or even a firm commitment. Details such as information on failure rates, tool requirements, or the actual availability of mock-ups can only be assured through a framework of contractual arrangements. These agreements are being established on recent engine programs. The success of these efforts must be evaluated, however, against the R&M environment on the program. One suspects the interface agreements have evolved while R&M priority is still lacking.

The subgroup of Specify Close Location of Screen affects the FOD mode. The closer the screen is to the actual engine intake, the less opportunity there is for maintenance-induced FOD sources. Several engines have had problems with gaps or failed (therefore loose) hardware in the ducting or adapters between the screen and the engine. One method of assuring this is the assignment of the screen design to the engine manufacturer. This decision cannot be reached until the potential of particle separators to preclude FOD is understood.

The subgroup which is most affected by the Particular baseline is Specify Pod-Mounted Engines. The assumptions which lead to the large benefits shown on the Particular baseline (Figure 39) are an all-axial-flow compressor and no particle separator. Under these assumptions, the manner by which the engine is installed in the airframe can have the significant impact shown. Experience has shown that the pod mounting of engines allows the natural downwash of the rotors to serve as an inertial separator, while an installation where the engines are more close coupled and integral to the airframe can act as a shelf or funnel for debris into the engine.

The desirability of pod-mounted engines has been reinforced, if not dominated, by its survivability advantages. It appears that pod-mounted engine designs are being selected on new aircraft programs. Little further customer actions appear necessary.

The subgroup of Provide Adequate Control Protection Devices is relatively small and consists of systems that could preclude or reduce overtemperature incidents.

The realization of this entire group is primarily the responsibility of the airframe manufacturer. The engine manufacturer, however, has a key role in generating information on predicted component failure rates and engine operational characteristics. Also, he can provide a vital motivating role in many of these areas that may compromise the basic airframe design. Although not a large benefit, this group should continue to be implemented by the customer. Aside from the benefits to generally mature R&M characteristics shown in this report, closer airframe and engine cooperation could avoid some of the early developmental problems which can plague an engine program.

De-Emphasis on Acquisition Costs

There are two subgroups to this remedial action group which represent the two design areas that could be benefited by a De-Emphasis on Acquisition Costs. These two subgroups are:

Preclude Use of Pneumatic Fuel Controls

This subgroup is the benefit if the design approach of pneumatic fuel controls was not permitted, nor encouraged, by an emphasis on low acquisition costs. A pneumatic fuel control was utilized on one model of the engines studied and proved to be extremely unreliable.

Require Integrally Cast Nozzle Assembly

This subgroup represents the R&M improvement possible if the design approach of integrally cast turbine nozzle assemblies was required and encouraged through a reduction in emphasis on low acquisition costs. This design feature was discussed in detail in the remedial action group of Provide Greater Flexibility in Scheduling. This feature was also considered in that group since the pressures of both time and costs have been cited as the prime restraints to its incorporation.

These two design features contribute to the benefits of the total group as shown in tabular form on Table XX, where the maximum benefit is shown for both the Composite and Particular engines in both the Index Number and UER parameters. These values are shown in graphical form in Figure 40 for the Composite engine and in Figure 41 for the Particular engine.

TABLE XX. REMEDIAL ACTION SUBGROUPS FOR DE-EMPHASIS ON ACQUISITION COST

Remedial Actions	Maximum Benefit			
	Composite		Particular	
	Index	UER	Index	UER
Preclude Use of Pneumatic Fuel Control	.56	.012	8.28	.180
Require Integrally Cast Nozzle Assembly	.52	.014	1.50	.042
Total	1.08	.026	9.78	.222

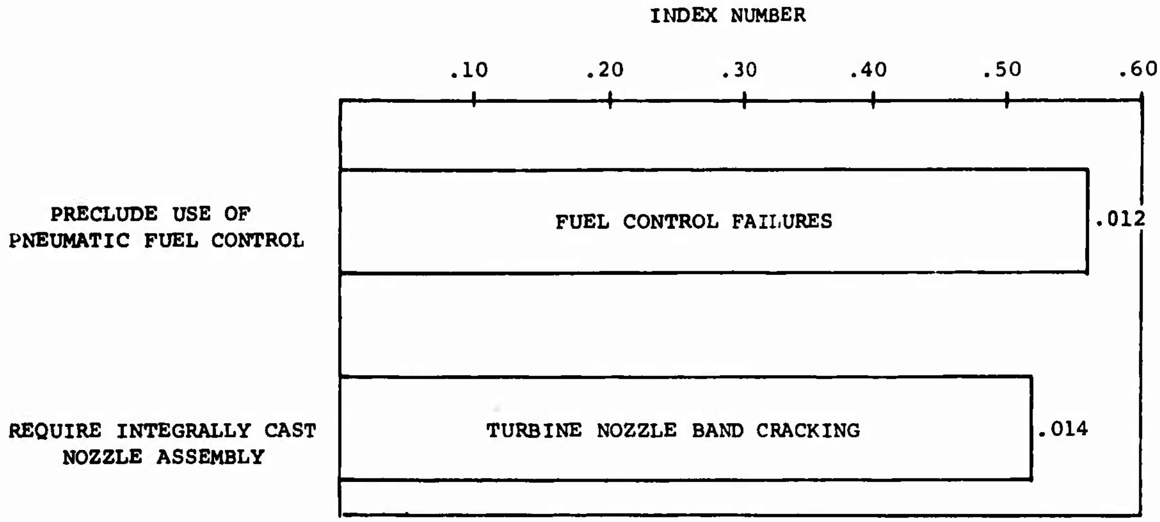

Figure 40. Remedial Action Subgroups for De-Emphasis on Acquisition Cost for Composite Baseline.

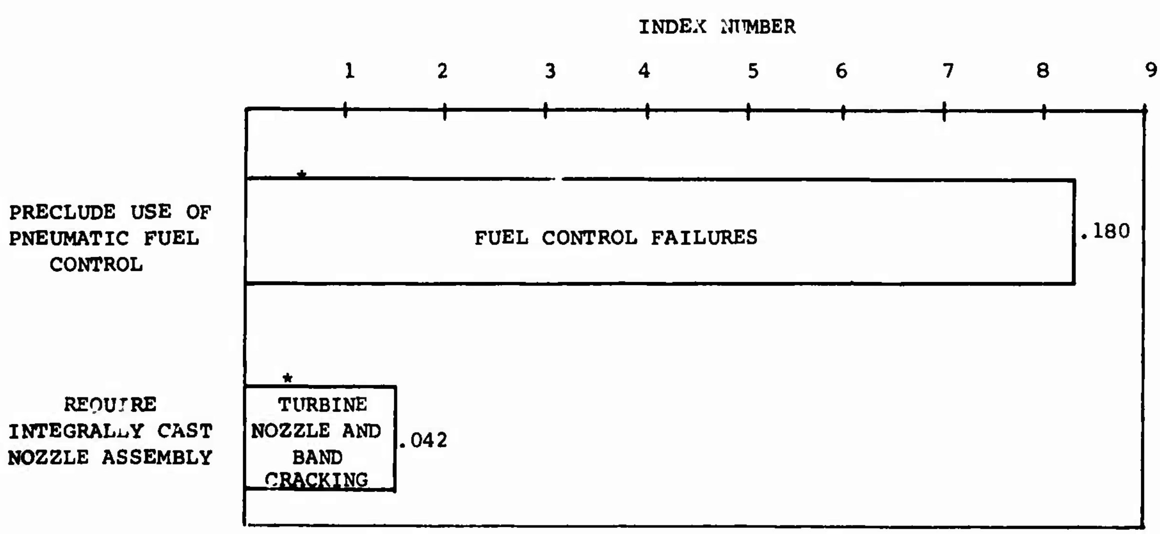

Figure 41. Remedial Action Subgroups for De-Emphasis on Acquisition Cost for Particular Baseline.

The greater increase in the benefit of the subgroup of Preclude Use of Pneumatic Fuel Control as opposed to the other subgroup in going from the Composite to the Particular engine is due, as suggested earlier, to the fact that only one engine utilized the pneumatic fuel control. Most of the engines of those examined experienced turbine nozzle inner or outer band cracking. The subgroup of Preclude Use of Pneumatic Fuel Control is a benefit that appears to be inevitable. On the one engine which utilized this design approach, a subsequent change was made to a traditional hydromechanical type, and there do not appear to be any other fuel controls of this type being proposed for future engines.

Similarly, the benefits of Integrally Cast Nozzles also appear inevitable. As discussed in the remedial action group of Provide Greater Flexibility and Scheduling, this feature is being incorporated on current engines. This design feature raises a paradoxical question. Since its incorporation requires higher initial tooling costs, small quantities of engines that must amortize these higher costs possess higher total acquisition costs. In reality, however, with any significant production base, integrally cast nozzles will ultimately produce lower acquisition costs. Since procurement selection policies have traditionally been based on acquisition costs of first quantity buys, the integrally cast nozzles have appear to have a cost disadvantage. If this phenomenon is recognized and design-to-cost efforts focus on the longer term acquisition cost, this more reliable design feature will assume the image of a desirable feature when low acquisition cost is desired and should solidify its incorporation in future engines.

It may be surprising to some that this remedial action group had such a low potential R&M benefit. Although the authors shared the common view that reliability and maintainability has been severely compromised because of acquisition cost emphasis, the above two design features were the only specific areas that could be identified where this effect was realized. When each of the three engine manufacturers that participated in these engine reliability studies were asked what engine characteristic would be most effective by increased emphasis on R&M, each manufacturer cited cost. Since little detailed support could be provided for this position, the authors are led to the conclusion that there is some confusion between true acquisition cost and amortized development cost. Many of the remedial action groups identified in this report (Testing, Increased Use of Analytical Procedures, Emphasis on R&M in Requirements, etc.)

will require considerable development costs to incorporate. These costs are development in nature and nonrecurring in practice and should not be viewed as contributing to a higher acquisition cost.

The one exception to this general position is the incorporation of adequate inlet protection, including both particle separators and screens which have both a development and recurring acquisition cost impact. The incremental cost for these features becomes even less obvious as the trend to integral designs becomes a reality. In this case, customer vigilance is required to assure that the O&M cost reduction potential of these features is considered and the full value of these features recognized. For the remainder of the engine design, continuation of the current emphasis on low acquisition cost does not appear to significantly compromise improved R&M.

Additional Quality Control Effort

No subgroups were established for this remedial action group. As additional quality control efforts were considered against the various failure modes of the engine, no particular pattern emerged that would allow subgroup definition. As shown in Appendix II, Summarization of Remedial Action, a variety of many failure modes contribute to the total benefit for this group.

Overall additional effort in the control of detail material properties contributes over half of the total benefit. Improved quality in assembly procedures is the remainder. The difference between the Composite and Particular engine baseline values shown on Table IX is due to only one failure mode that appeared on one specific engine. Other than this one failure mode, additional quality control effort could benefit all engines equally, regardless of configuration, manufacturer, or military customer.

Participation by the customer in initiating these benefits must be directed at the quality control program on specific engine programs. The potential for new technology in this quality control area was previously discussed in the remedial action group of Improved Technology.

This emphasis on specific programs will undoubtedly have a cost impact that could be considerable and should be recognized by the procuring agencies. Whether the benefits shown on Table IX are worth the potential cost is not readily apparent to the authors. The most likely situation is that they may be cost effective in themselves, but not nearly as cost effective as some of the other remedial actions previously discussed and possessing greater potential benefits and obviously more manageability.

Greater Control of Operation of Engine

Three subgroups are established for this remedial action group. These three subgroups are:

Improvement in General Operations

This subgroup reflects benefits if a general improvement was realized in the operation of the engine/aircraft. Similar to the General Improvement subgroup in Improved Maintenance, this subgroup is utilized where no specific corrective action is envisioned. Calculation of benefits for this subgroup do not assume that these improvements are either viable or practical and were created as a subgroup only to represent the benefits as radical improvements were realized in the skill and attitude of aviators.

Control Aircraft Exposure to Extreme Environments

This subgroup represents the benefits that are within the control of the aviator through a greater application of discretion on landing sites. Calculation of benefits recognizes the reality that aviators can exercise judgement only in limited cases.

Adhere to Engine Shutdown Procedures

This subgroup relates to the actual operation of the engine rather than the total aircraft. Specifically, it reflects the benefits if the shutdown procedures for each engine were followed explicity.

These subgroups contribute to the remedial action group of Greater Control of Operation of Engine, as shown in tabular form in Table XXI for both the Particular and Composite baselines for both the Index Number and UER values, and in graphical form in Figure 42 for the Composite engine and in Figure 43 for the Particular engine.

TABLE XXI. REMEDIAL ACTION SUBGROUPS FOR CLOSER CONTROL OF OPERATION OF ENGINE				
	MAXIMUM BENEFIT			
	COMPOSITE		PARTICULAR	
Remedial Actions	INDEX	UER	INDEX	UER
Improvement in General Operations	.57	.030	.57	.030
Control Aircraft Exposure to Extreme Environments	.10	.005	.10	.005
Adhere to Engine Shutdown Procedures	.03	.001	1.68	.042
Total	.70	.036	2.35	.077

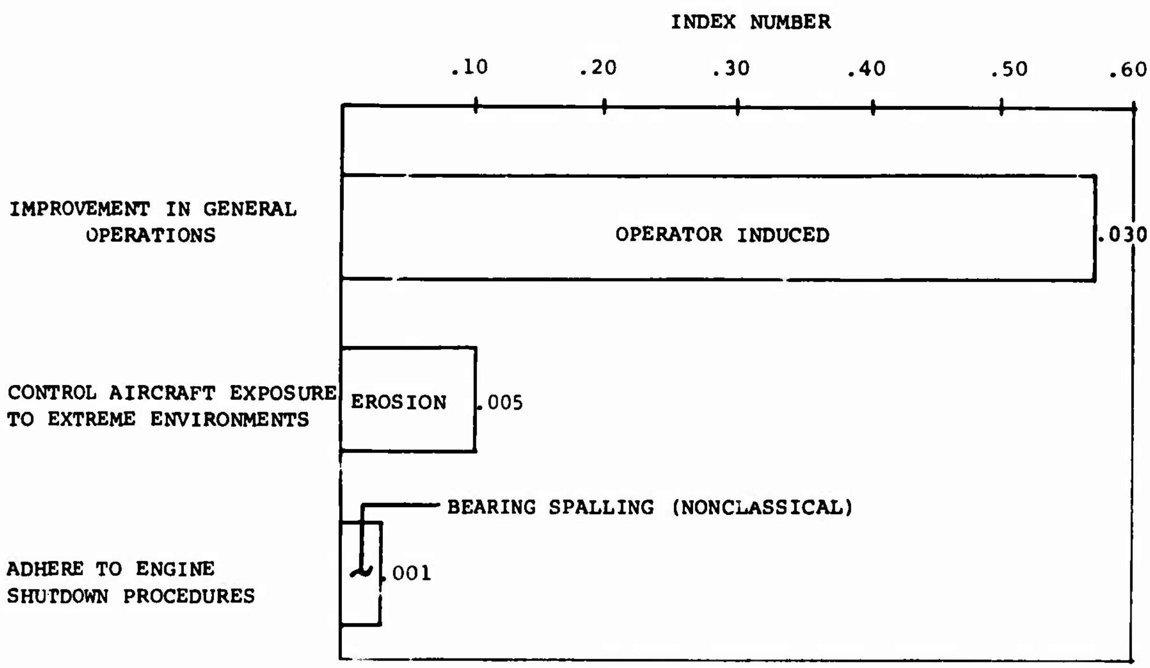

Figure 42. Remedial Action Subgroups for Closer Control of Operation of Engine for Composite Baseline.

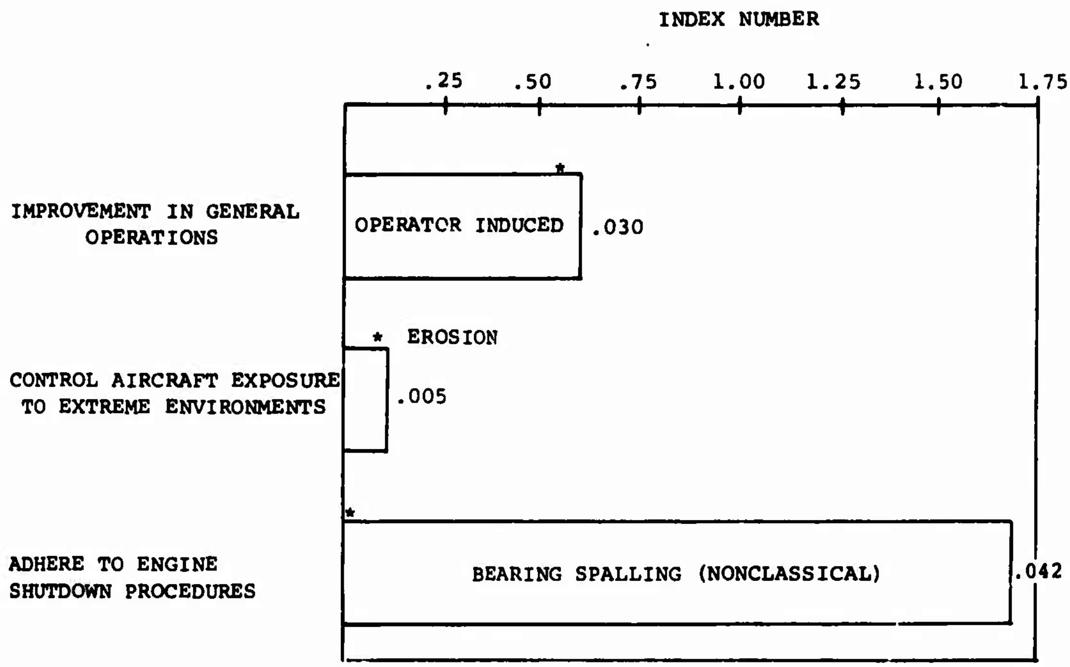

Figure 43. Remedial Action Subgroups for Closer Control of Operation of Engine for Particular Baseline.

The most obvious change in prioritization between the Composite and the Particular baselines is the nearly sixtyfold increase in the magnitude of the Adhere to Engine Shutdown Procedures subgroup. This is due to the fact that only one bearing in one engine possessed a problem which was directly related to engine shutdown procedures. This bearing problem was caused when insufficient dwell time was spent at ground idle speeds and an oil coking condition resulted from the excessive oil temperatures.

The other two subgroups did not increase significantly from the Composite to the Particular engine since the problems these subgroups addressed are generally consistent among the study engines.

In general, this subgroup display presents a discouraging perspective. Over eighty percent of the potential benefit against the Composite baseline is due to the improvement in the general subgroup. Realization of this benefit would undoubtedly incur a cost of considerable magnitude. Implementation of the second subgroup, Control Aircraft Exposure to Extreme Environments, may be a more manageable remedial action

but provides insignificant benefits. This entire group does not appear to be a likely candidate for customer activity until other more cost effective remedial actions have been initiated and extremely high R&M is essential.

CONCLUSIONS

CAUSAL FACTOR ANALYSIS

The analysis of Causal Factors, through the process of identifying lower-level Factor Elements, led to the following conclusions:

Most of the contribution to the R&M problem by the Causal Factors of Specification and Requirements and Preliminary Design is due to a relatively few specific sources, and these sources are readily controllable by customer action on specific aircraft programs.

A significant portion of the problem caused by Design Execution is not easily resolved. A range of remedial actions is appropriate across many failure modes, where much of the improvement will not be readily visible.

The problems caused by Manufacturing and Quality Control have a few failure modes which appear as candidates for improved technology.

Improvements that are directed at the problems caused by Operations and Maintenance must be of a very general or comprehensive nature to have any real impact.

REMEDIAL ACTION ANALYSIS

The analysis of remedial actions led to the following conclusions:

Although many failure modes can be resolved through a variety of remedial actions, certain modes can only be addressed very early in a production program. Many of these modes are the highest contributors to the R&M problem.

In arranging specific remedial actions into groups, it becomes clear that most remedial actions are related to specific engine programs, where decisions concerning priorities between performance, weight, costs, and R&M must be addressed conclusively.

The additional emphasis given to certain remedial actions by the Particular engine baseline reinforces the previous conclusion that the decisions on specific engine programs are the most important.

Testing is the highest ranked remedial action and perhaps the least understood. The benefits of extended duration as

opposed to improved execution are pivotal to customer implementation of this remedial action.

A key element in the implementation of most remedial action groups is the time phasing of initiation requirements. Figure 44 illustrates the general magnitude of 10 remedial action benefits on a time scale of a specific engine program. It indicates how most of the remedial actions must be initiated at very early stages of the engine program.

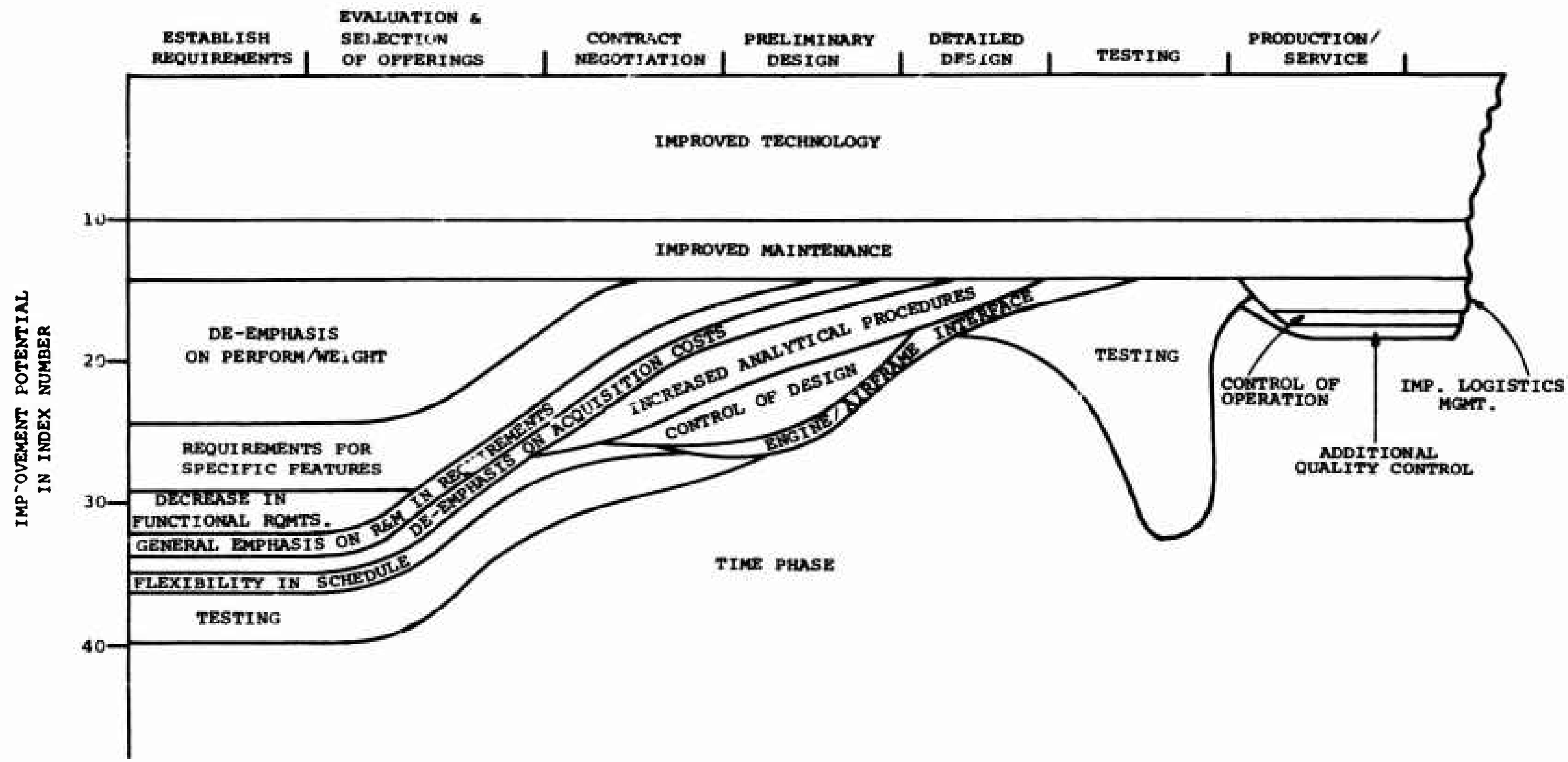

Figure 44. Time Phasing of Remedial Action Initiation.

RECOMMENDATIONS

The priorities for engine characteristics (performance, cost, R&M, etc.) must be established early in the program and clearly expressed in terms of both compatible numerical objectives and the development costs and schedules appropriate to these objectives. R&M recovery in the absence of this will be difficult if not impossible.

The performance, weight, and cost penalties of certain design approaches favorable to R&M should be quantified and disseminated widely for general consensus. The following areas have highest priority:

- Axial versus axial/centrifugal compressor
- Labyrinth versus positive-contact seals
- An anti-iced inlet-protection screen

The state of the art should be assessed on the following design areas and the analysis widely distributed:

- Air bearings
- Various types of contacting or partially contacting oil seals
- Roller skidding phenomenon
- Compressor resonance analysis methods
- FOD resistance of particle separators

Recent engine/airframe interface agreements should be reviewed to determine areas of success or failure in both contractual and technical areas.

A general study of engine maintenance should be undertaken to determine specific remedial actions of a general nature. Attention should focus on the differences between the military and commercial experience.

Greater cooperation between the logistics and product assurance communities should be encouraged in order to make maximum practical use of evolving techniques for calculations of spares requirements.

An in-depth analysis of engine development testing should be undertaken by an engine manufacturer to identify the specific actions that must be accomplished during the test program in order to achieve the maximum R&M benefit. The analysis should also address the cost schedule and contractual obligations that such improvements would impose on specific engine programs.

LITERATURE CITED

1. Rummel, K. G., and Smith, H. J. M., INVESTIGATION AND ANALYSIS OF RELIABILITY AND MAINTAINABILITY PROBLEMS ASSOCIATED WITH ARMY AIRCRAFT ENGINES, Boeing Vertol Company, USAAMRDL Technical Report 73-28, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, August 1973, AD772950.

2. A STUDY OF THE AIR FORCE JET ENGINE MAINTENANCE PROGRAM REPORT, ARINC Research Corporation, 30 May 1970.

3. A STUDY OF THE AIRCRAFT ENGINE ACQUISITION PROCESS, Joint AMC/NMC/AFCC/AFSC Commanders' Panel on Aircraft Engine Acquisition, 5 February 1971.

4. Paladini, W., STATIC AND ROTATING AIR/GAS SEAL EVALUATION, Curtiss-Wright Corporation, USAAMRDL Technical Report 71-28, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, June 1971, AD730361.

5. Scoppe, Frank E., ADVANCED TORQUE MEASUREMENT SYSTEMS TECHNIQUE FOR AIRCRAFT TURBOSHAFT ENGINES, Avco Lycoming Division, USAAMRDL Technical Report 73-37, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, June 1973, AD771965.

APPENDIX I
IDENTIFICATION AND QUANTIFICATION OF REMEDIAL ACTIONS

TABLE XXII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: LACK OF REQUIREMENT FOR FEATURES

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Foreign-Object Damage	3.70 / 6.71	.217 / .388	Require installation of engine inlet screens	Particular	W/Axial W/O Sep	W/Centrf W/Sep	34.59	2.000	2.59	.150
			(Require Specific Features)	Composite			2.35	.138	2.35	.138
			Require installation of inlet particle separator	Particular	W/Axial W/O Screen	W/Centrf W/Screen	29.45	1.700	.86	.050
			(Require Specific Features)	Composite			2.04	.120	2.04	.120
			Utilize axial/centrifugal over axial flow compressors	Particular	W/O Screen W/O Part Sep	W/Screen W/Part Sep	25.94	1.500	5.19	.300
			(De-emphasis on Perf/Wt)	Composite			4.05	.238	4.05	.238
Erosion	1.22 / 2.90	.058 / .140	Require installation of inlet particle separators	Particular	W/Axial	W/Centrf	155.55	7.500	3.73	.180
			(Require Specific Features)	Composite			.68	.040	.68	.040
			Utilize axial/centrifugal over axial flow compressors	Particular	W/O Sep	W/Sep	261.46	7.800	.83	.040
			(De-emphasis on Perf/Wt)	Composite			1.53	.090	1.53	.090

TABLE XXIII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: PERFORMANCE/WEIGHT EMPHASIS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Foreign-Object Damage	1.00 / 6.71	.055 / .388	Require installation of inlet protection screens	Particular	W/Axial W/O Sep	W/Centrif W/Sep	34.59	2.000	2.59	.150
			(Require Specific Features)	Composite			2.3[illegible]	.138	2.35	.138
			Require installation of inlet particle separations	Particular	W/Axial W/O Screen	W/Centrif W/Screens	29.45	1.[illegible]00	.86	.050
			(Require Specific Features)	Composite			2.04	.120	2.04	.120
			Utilize axial/centrifugal over axial flow compressors	Particular	W/O Screen W/O Part Sep	W/Screens W/Part Sep	25.94	1.500	5.19	.300
			(De-emphasis on Perf/Wt)	Composite			4.05	.238	4.05	.238
Erosion	.81 / 2.90	.040 / .140	Require installation of inlet particle separators	Particular	W/Axial	W/Centrif	155.35	7.500	3.73	.180
			(Require Specific Features)	Composite			.68	.040	.68	.040
			Utilize axial/centrifugal over axial flow compressors	Particular	W/O Sep	W/Sep	161.46	7.800	.83	.040
			(De-emphasis on Perf/Wt)	Composite			1.53	.090	1.53	.090

TABLE XXIII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Turbine Blade/Wheel Cracking	$\frac{.70}{1.17}$	$\frac{.001}{.001}$	Require adequate low-cycle fatigue life	Particular	70% eff	40% eff	.50	.001	.30	.000
			(De-emphasis on Perf/Wt)	Composite			.40	.001	.40	.001
Carbon Seal Leakage	$\frac{.65}{3.28}$	$\frac{.038}{.189}$	Specify use of labyrinth seals	Particular	T58 Rates	T64 Rates	12.98	.750	.87	.050
			(De-emphasis on Perf/Wt)	Composite			3.19	.183	3.19	.183
Compressor Vane Erosion Failures	$\frac{.50}{1.11}$	$\frac{.013}{.0[illegible]8}$	Utilize axial/centrifugal over axial flow compressor	Particular	T64 Rates	T58 Rates	9.91	.250	1.98	.050
			(De-emphasis on Perf/Wt)	Composite			.50	.013	.50	.013

TABLE XXIV. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: ACQUISITION COST EMPHASIS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Fuel Control Failure	.43 / 2.58	.009 / .058	Preclude use of pneumatic fuel control	Particular	T63 Rates comp to hyd/mech	T63 Rates in OH-6	8.28	.180	3.50	.075
			(De-emphasis on cost in requirements)	Composite			.56	.012	.35	.008
Turbine Nozzle Band Cracking	.11 / .57	.005 / .016	Require integrally cast nozzles	Particular	T53 Rates	Lowest Rate Eliminated	1.50	.042	.07	.002
			(De-emphasis on cost in requirements)	Composite			.52	.014	.11	.005

TABLE XXV. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: REQUIREMENT FOR SPECIFIC FEATURES

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Fuel Control Failures	$\frac{.40}{2.58}$	$\frac{.008}{.058}$	Eliminate requirement for power management systems	Particular	Bad accessibility of T58 in CH-46	Good accessibility of T58 in H-3 and detail design improvement	9.70	.21	2.76	.060
			(Decrease functional requirements)	Composite			1.48	.032	.88	.019
High-Speed Torquemeter	$\frac{.24}{1.21}$	$\frac{.009}{.046}$	Eliminate requirement for high-speed power output	Particular	T55 rates w/mech torquemtr	Elec sys incorp with rate of .006	5.91	.225	.05	.002
			(Decrease functional requirements)	Composite	one engine with mech to all with hyd/mech	-	1.14	.043	-	-

TABLE XXVI. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: PROGRAM SCHEDULE

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Compressor Blade/Disc Fatigue Failures	.74 / 2.40	.002 / .006	Allow Adequate Time for Configuration Changes in Growth Models	Particular	T53 Rates	60% eff of use of time on T53	2.10	.005	1.30	.003
			(Greater Flexibility in Scheduling)	Composite	T53 Impact	30% eff on impact	.74	.002	.20	.001
Turbine Nozzle Band Cracking	.16 / .57	.001 / .016	Allow time for development of castings (tooling) for integrally cast nozzles	Particular	T53 Rates	50% eff on T63	1.50	.042	.071	.002
			(Greater flexibility in scheduling)	Composite	80% eff	30% eff	.52	.014	.11	.005

TABLE XXVII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: SPECIFICATIONS & REQUIREMENTS
FACTOR ELEMENT: GENERAL LACK OF R&M EMPHASIS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	$\frac{.51}{5.09}$	$\frac{.031}{.305}$	Give greater consideration to maintainability durability	Particular	T58 Total Removal Rates	T74 Total Removal Rates	2.55	.15	3.50	.020
			(Emphasis on R&M in requirements)	Composite	50% of experienced range	10% of experienced range	.85	.05	.17	.01
Power Train Reduction	$\frac{.29}{.72}$	$\frac{.005}{.013}$	Require higher reliability in gearbox bearings and seals	Particular	50% eff on worst rate	20% eff on best rate	.39	.007	.05	.001
			(Emphasis on R&M in requirements)	Composite	80% improvement	20% improvement	.20	.004	.05	.001
Operator Induced	$\frac{.25}{2.54}$	$\frac{.012}{.122}$	Give greater consideration to engine and operations	Particular	T63 rates 100% improvement	Smallest rates 40% improvement	2.52	.120	.084	.004
			(Emphasis on R&M in requirements)	Composite	100% improvement	40% improvement	.25	.012	.100	.005

TABLE XXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Combustion Housing Corrosion	.25 .58	.009 .020	Greater consideration should be given to environmental conditions	Particular	T58 Rates 80% eff	T55/T63 Rates	1.45	.050	.00	.000
			(Emphasis on R&M in requirements)	Composite	80% eff	20% eff	.20	.007	.05	.002
Exhaust Components	.24 .55	.002 .004	Greater consideration should be given to airframe vibration environment	Particular	(mid-exhaust engines) 80% eff	T53/T64 Rates 40% eff	.35	.003	.03	.000
			(Emphasis on R&M in requirements)	Composite	80% eff	40% eff	.19	.002	.10	.001
Bearing Spalling Classical (Bid)	.20 .42	.003 .006	Require higher B_{10} lives on bearings	Particular	T63 Rates 100% eff	Best Rate	1.40	.025	.00	.000
			(Emphasis on R&M in requirements)	Composite	90% eff	60% [illegible]	.18	.003	.12	.002

TABLE XXVIII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: ENGINE/AIRFRAME PHYSICAL INTERFACE

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Erosion	$\frac{.15}{2.90}$	$\frac{.007}{.140}$	Specify pod-mounted engines	Particular	Unprotected axial (RVN)	Protected centrif. (CONUS)	20.71	1.00	.21	.01
			(Additional control of interface)	Composite			.150	.007	.10	.005
Improper Maintenance	$\frac{.06}{5.09}$	$\frac{.003}{.305}$	Accessibility to all accessories should be specified	Particular	T58 Rates 100% eff	20% eff	.15	.007	.00	.000
			(Additional control of interface)	Composite			.06	.003	.03	.000

TABLE XXVIII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Fuel Control Failures	$\frac{.38}{2.58}$	$\frac{.006}{.058}$	Accessibility to all accessories should be specified	Particular	T58 Rates	Good Access	5.87	.130	.00	.000
			(Additional control of interface)	Composite	100% eff	30% eff	.38	.006	.13	.002
Operator Induced	$\frac{.25}{2.54}$	$\frac{.012}{.122}$	Specify engine control protection devises	Particular	T63 Rates 50% eff	Best Rates 10% eff	1.20	.060	.20	.01
			(Additional control of interface)	Composite	50% eff	10% eff	.120	.006	.020	.001
Airframe Related	$\frac{.23}{2.36}$	$\frac{.015}{.148}$	Specify accessibility to all airframe mounted equipment without removal of engine	Particular	T58 Rates 100% eff	Best Rates 20% eff	.64	.040	.08	.005
			(Additional control of interface)	Composite	100% eff	20% eff	.23	.015	.04	.003
Foreign-Object Damage	$\frac{.20}{6.17}$	$\frac{.013}{.388}$	Specify close location of screen to engine inlet and pod mounting of engines	Particular	Both pod mtg. & screen design on axial engine	Particle Separator & cent comp.	.14	.008	.00	.000
			(Additional control of interface)	Composite			.20	.013	.10	.006

TABLE XXIX. IDENTIFICATION & QUANTIFICATION C REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: OVERALL ENGINE CONFIGURATION

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	.06 / 5.09	.003 / .305	Require gas path internal to main casing	Particular	T63 Rates	-	.16	.006	-	-
			(Control of Designs)	Composite	100% eff	50% eff	.06	.003	.03	.002
Bearing Spalling (Nonclassical)	.26 / 1.86	.004 / .033	Preclude placement of bearings in hot section and use of differential bearings	Particular	T63 #8 Bearing Rate	-	1.26	.018	-	-
			(Control of Designs)	Composite	70% eff	30% eff	.20	.002	.06	.001

TABLE XXX. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: DESIGN CONCEPT

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Carbon Seal Leakage	$\frac{.72}{3.28}$	$\frac{.042}{.189}$	Require labyrinth seals	Particular	See Specifications And Requirements		12.98	.75	.87	.05
			(De-emp. on Perf./Wt.)	Composite			3.19	.183	3.19	.183
Foreign-Object Damage	$\frac{.44}{6.71}$	$\frac{.023}{.388}$	Require centrifugal compressors	Particular			25.94	1.50	5.19	.30
			(De-emp. on Perf./Wt.)	Composite			4.05	.238	4.05	.238
Fuel Control Failure	$\frac{.38}{2.58}$	$\frac{.006}{.058}$	Preclude use of penumatic fuel control	Particular			8.28	.180	3.50	.075
			(De-emphasis on costs)	Composite			.56	.012	.35	.008
Erosion	$\frac{.29}{2.90}$	$\frac{.014}{.140}$	Require a centrifugal compressor	Particular			161.46	7.800	.83	.040
			(De-emphasis on perf./Wt.)	Composite			1.53	.090	1.53	.090
High-Speed Torquemeter	$\frac{.24}{1.21}$	$\frac{.009}{.046}$	Require an electrical torquemeter	Particular	Worst hi-speed mech.	No value over low speed	5.83	.222	-	-
			(Control of designs)	Composite			1.13	.043	1.13	.043

TABLE XXXI. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: DETAIL DESIGN CONFIGURATION

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Lubrication Pump Failures	.20 / .60	.005 / .017	Insure that valving in lubrication system precludes pump flooding (Control of Designs)	Particular	T58 Rates		.60	.015	-	-
				Composite	100% eff	30% eff	.20	.005	.07	.001
Environmental	.11 / 1.09	.006 / .059	Insure adequate lube filtration when using labyrinth seals (Control of Designs)	Particular	T58 Rates	-	1.00	.05	-	-
				Composite	80% eff	20% eff	.08	.004	.030	.002
Bearing Spalling (Nonclassical)	.02 / 1.86	.001 / .033	Provide adequate guidance for shafts into bearings (Control of Designs)	Composite			.02	.001	-	-

TABLE XXXII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: INTERNAL ARRANGEMENT

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	In [illegible]	UER			Maximum	Minimum	Index	UER	Index	UER
Lubrication Pump Failures	.07 / .60	.003 / .017	Require pump to be placed outside gearbox	Particular	T63 Rates		.10	.005	-	-
			(Control of designs)	Composite	100% eff	40% eff	.07	.003	.03	.001
Improper Maintenance	.06 / 5.09	.003 / .305	Preclude simultaneous precise and gross assembly techniques (Control of Designs)	Composite	80% eff	30% eff	.05	.002	.02	.001

TABLE XXXIII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: MATERIAL SELECTION

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Environmental	.11 / 1.09	.006 / .059	Preclude use of magnesium	Particular	T55 Rates		.40	.020	-	-
			(Control of Designs)	Composite	100% eff	Assume improvement in coating 50%	.11	.006	.05	.003
Improper Maintenance	.07 / 5.09	.006 / .305	Preclude use of plastic compressor lining	Particular	T63 Rates		.16	.012	-	-
			(Control of Designs)	Composite	100% eff	30% eff	.07	.006	.02	.002
			Use most corrosion resistant metals	Particular	Worst engine		.31	.028	-	-
			(Control of Designs)	Composite	100% eff	30% eff	.07	.006	.02	.002

TABLE XXXIV. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: PRELIMINARY DESIGN
FACTOR ELEMENT: MANUFACTURING APPROACH

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Compressor Blade/Disc Fatigue	$\frac{.20}{2.40}$	$\frac{.001}{.006}$	Preclude integrally cast blade/disc	Particular	T63 Rates	—	.40	.002	-	-
			(Control of Designs)	Composite	70% eff	LCF is adequate	.15	.001	.15	.001

TABLE XXXV. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: DESIGN EXECUTION
FACTOR ELEMENT: ANALYSIS AVAILABLE - NOT USED - REASONABLE COST & EFFECTIVENESS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Airframe Related	.95 / 2.36	.058 / .148	Consideration of the effects of aircraft equipment and installation	Particular	¼ of T58 80% eff	-	2.56	.160	-	-
			(Additional Analysis)	Composite	80% eff	30% eff	.76	.046	.29	.017
			Additional flight testing and bench testing with production accessories	Particular	¼ of T58 50% eff	-	1.60	.100	-	-
			(Additional Testing)	Composite	50% eff	20% eff	.48	.029	.19	.012
Accessory	.72 / .91	.020 / .025	Increased analysis on bearing and spacer restraint (Additional Analysis)	Composite	50% eff	20% eff	.36	.010	.12	.004
			Extend duration of test (Additional Testing)	Composite	60% eff	30% eff	.43	.012	.22	.006

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Fuel Control Failures	.60 / 2.58	.018 / .C58	Consideration of realistic maintenance environment (Additional Analysis)	Composite	50% eff	20% eff	.30	.009	.12	.003
			Use of realistic maintenance on mounting design of fuel control during testing (Additional Testing)	Composite	70% eff	40% eff	.42	.013	.24	.007
Compressor Blade/Disc Fatigue	.38 / 2.40	.001 / .006	Intensify analysis pertaining to potential resonant conditions	Particular	Comparison of T53 to AVG.	½ AVG. 60% eff	2.10	.005	.72	.002
			(Additional Analysis)	Composite	60% eff	30% eff	.23	.001	.12	.000
			Additional Testing including a spectrum of parts with production variations (Additional Testing)	Composite	60% eff	50% eff	1.44	.004	1.20	.003

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Bearing Spalling (Nonclassical)	.25 / 1.86	.004 / .033	Extended duration of test	Particular	8 times T63 #1 bearing	T58 Rates	24.41	.472	.57	.010
			(Additional Testing)	Composite	90% eff	40% eff	1.67	.030	.74	.013
			Analysis of oil flow characteristics, roller end radius, spline lockup effects (Additional Analysis)	Composite	60% eff	20% eff	.12	.002	.05	.001
Carbon Seal Leakage	.20 / 3.28	.012 / .189	Further investigation and design analysis concerning flatness of runner, oil scavenge, and the natural frequency of the bellows	Particular	T58 Rates 60% eff	Lab. seals	6.12	.36	-	-
			(Additional Analysis)	Composite	70% eff	20% eff	.14	.009	.04	.002
			Test with varying running speeds, a variety of reinstalled seals and complete lube system	Particular	T58 Rates	Lab. Seals	10.20	.60	-	-
			(Additional Testing)	Composite	90% eff	40% eff	.18	.010	.08	.005

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Operator Induced	$\frac{.20}{2.54}$	$\frac{.011}{.122}$	Additional Analysis of potential operator techniques (Additional Analysis)	Composite	50% eff	20% eff	.10	.005	.04	.002
			Perform tests with normal operator technique (emphasis on flight test) (Additional Analysis)	Composite	60% eff	30% eff	.12	.007	.06	.003
High-Speed Torquemeter	$\frac{.20}{1.21}$	$\frac{.009}{.048}$	Analyze the possible damage of parts due to maintenance	Particular	1/6 of T55 80% eff	Low Speed	.88	.03	-	-
			(Additional Analysis)	Composite	50% eff	20% eff	.10	.005	.04	.002
			Include realistic maintenance during testing as well as extended duration	Particular	1/6 of T55	Low Speed	1.10	.04	-	-
			(Additional Testing)	Composite	70% eff	30% eff	.14	.006	.06	.003

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Foreign-Object Damage	$\frac{.20}{6.71}$	$\frac{.012}{.388}$	Give increased consideration to engine/screen interfaces (Additional Analysis)	Composite	50% eff	20% eff	.10	.006	.04	.002
			Operate with production inlet protection during testing (Additional Testing)	Composite	90% eff	50% eff	.18	.011	.10	.0[illegible]
Bearing Race Rotation Displacement	$\frac{.20}{.61}$	$\frac{.011}{.032}$	Analyze for the Potential of race rotation or displacement (Additional Analysis)	Particular	T55 Rates 80% eff	-	2.10	.12	-	-
				Composite	80% eff	40% eff	.16	.009	.08	.005

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Lubrication Pump Failures	.16 / .64	.005 / .017	Consider combinations and sequencing of failures in lube system design	Particular	T58 Rates 70% eff	20% eff	1.50	.05	.36	.01
			(Additional Analysis)	Composite	70% eff	20% eff	.11	.003	.03	.001
			Include production aircraft lube system for testing and extend duration	Particular	T58 Rates 90% eff	50% eff	1.80	.06	.90	.03
			(Additional Testing)	Composite	90% eff	50% eff	.15	.005	.08	.002
Bearing Cage Wear Cracking	.15 / .50	.004 / .018	Examine thermal effects of expansion rate and its effect on bearing loads	Particular	T64 Rates 50% eff	-	.68	.025	-	-
			(Additional Analysis)	Composite	50% eff	30% eff	.07	.002	.05	.001
			Utilize anti-icing features and complete cycling during testing (Additional Testing)	Composite	80% eff	40% eff	.12	.003	.06	.001
			Development of Air bearings (Improved Technology)	Composite	100% eff	100% eff	.50	.018	.50	.018

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Power Train Reduction	$\frac{.15}{.72}$	$\frac{.003}{.013}$	Increase concentration in the area of outer race retention (Additional Analysis)	Composite	50% eff	20% eff	.07	.001	.03	.001
			Extend duration of testing with accessories loaded as appropriate (Additional Testing)	Composite	90% eff	50% eff	.14	.002	.07	.001
Lubrication Filters/Coolers	$\frac{.13}{.26}$	$\frac{.002}{.004}$	Consider combinations and sequences of lube system failures	Particular	T58 Rates 70% eff	-	.70	.01	-	-
			(Additional Analysis)	Composite	70% eff	20% eff	.09	.002	.03	.000
			Provide maintenance and vibration environment during testing	Particular	T58 Rates 80% eff	-	1.30	.02	-	-
			(Additional Testing)	Composite	80% eff	50% eff	.11	.002	.06	.001

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Turbine Support Structure and Fittings	.12 / .54	.006 / .025	Analyze loads arising from external drive shafting (Additional Analysis)	Composite	40% eff	10% eff	.05	.002	.01	.001
			Test with external shafting and aircraft vibration levels (emphasis on flight test) (Additional Testing)	Composite	60% eff	30% eff	.07	.004	.03	.002
Turbine Blade/Wheel Cracking	.11 / 1.17	.001 / 001	Increase emphasis and analysis of low-cycle fatigue and potential resonance (Additional Analysis)	Composite	50% eff	30% eff	.05	.001	.02	.000
			During testing, use accelerated aging test and speed resonance search Parts should have manufacturing variations (Additional Testing)	Composite	60% eff	40% eff	.70	.001	.47	.000

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	.10 / 5.09	.006 / .305	Murphy-proof existing configurations (consider potential maintenance damage) (Additional Analysis)	Composite	80% eff	10% eff	.08	.005	.01	.001
			Use realistic maintenance procedures during testing (Additional Testing)	Composite	60% eff	40% eff	.06	.004	.04	.002
Combustion Swirl Cup Problems	.10 / .17	.004 / .006	Give additional consideration to the effect of tolerance buildup	Particular	80% eff of T55	20% eff of T55	1.20	.040	.30	.010
			(Additional Analysis)	Composite	80% eff	20% eff	.08	.003	.02	.001
			Test with extremes in variability of component dimensions	Particular	T55 Rates 90% eff	50% eff	1.40	.05	.65	.02
			(Additional Testing)	Composite	90% eff	50% eff	.09	.003	.05	.002

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Cases Secondary Structure Cracking	$\frac{.08}{.45}$	$\frac{.003}{.017}$	Consider vibration effect upon riveted assembly and analyze in depth	Particular	T58 Rates	-	1.50	.06	-	-
			(Additional Analysis)	Composite	50% eff	20% eff	.04	.002	.02	.001
			Test with aircraft vibration and external shafting	Particular	T58 Rates	-	1.50	.06	-	-
			(Additional Testing)	Composite	70% eff	40% eff	.06	.002	.03	.001
			Preclude use of rear drive engine	Particular	T58/T73 thin wall	T58/T73 thick wall	3.38	.13	.52	.02
			(Control of Designs)	Composite	Average of front drive engine	-	.39	.015	-	-
Combustion Housing Corrosion Fittings	$\frac{.07}{.58}$	$\frac{.002}{.020}$	Give consideration to subsequent manufacturing operations and maintenance damage in calculating	Particular	T58 Rates 70% eff	-	2.52	.08	-	-
			(Additional Analysis)	Composite	70% eff	20% eff	.05	.001	1.01	-
			Test using production manufacturing techniques and realistic vibration levels, maint. environment should also be maintained	Particular	T58 Rates	-	3.30	.11	-	-
			(Additional Testing)	Composite	90% eff	50% eff	.06	.002	.03	.001

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Electrical Ignition	.07 / .26	.002 / .005	Specify accessibility to all accessories (Additional Control of Engine/ Airframe Interface)	Composite	80% eff	20% eff	.06	.002	.01	.000
Turbine Shafts Couplings	.06 / .23	.001 / .003	Analyze output shaft misalignment, unbalance Effects of sharp radii should be considered (Increased Concentrations) (Additional Analysis)	Composite	60% eff	10% eff	.04	.001	.00	.000
			Utilize aircraft output shafting during testing (Additional Testing)	Composite	80% eff	50% eff	.18	.003	.12	.001

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Compressor Valve Erosions, Failures	.04/1.11	.001/.028	Increase analysis concerning material selection and the effect of erosion on fatigue strength	Particular	T64 Rates	-	.32	.008	-	-
			(Additional Analysis)	Composite	70% eff	30% eff	.03	.001	.012	-
			Test for fatigue strength after erosion tests	Particular	T64 Rates 70% eff	-	6.40	.16	-	-
			(Additional Testing	Composite	70% eff	50% eff	.77	.020	.56	.014
Compressor Diffuser Cracking	.03/.28	.002/.022	Consider deflections in assembly due to thermal growth and air pressure (Additional Analysis)	Composite	70% eff	20% eff	.02	.001	.01	-
			Additional cycling during testing (extend duration) (Additional Testing)	Composite	90% eff	50% eff	.03	.002	.02	.001

TABLE XXXV - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Exhaust	$\frac{.02}{.55}$	$\frac{.001}{.004}$	Give consideration to aircraft vibration on tail pipe mounting (Additional Analysis)	Composite	50% eff	20% eff	.01	.000	.00	.000
			Extend duration as well as include aircraft vibration (Additional Testing)	Composite	90% eff	50% eff	.02	.001	.01	.000

TABLE XXXVI. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: DESIGN EXECUTION
FACTOR ELEMENT: ANALYSIS AVAILABLE - NOT USED - NOT COST EFFECTIVE

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Bearing Spalling (Nonclassical)	.70 / 1.86	.012 / .033	A. Use of production variability of bearing housings, realistic cycling, and additional duration	Particular	T53 #2 bearing		2.12	.038	-	-
			B. Use of production oil systems in realistic heat scavenge							
			C. Use of production variability on splines and realistic temp cycling							
			(Additional Testing)	Composite	70% eff	20% eff	.49	.008	.14	.002
Carbon Seal Leakage	.60 / 3.28	.033 / .189	Use contaminated airflow, realistic maintenance procedures, and extended duration	Particular	Against T58 #5 seal	Lab. seals incl.	3.40	.200	-	-
			(Additional Testing)	Composite	90% eff	30% eff	.54	.030	.18	.010
Air Valve Binding, Leaking	.30 / .38	.006 / .007	Utilize contaminated ambient air during testing	Particular	Worst Rates	-	.42	.010	-	-
			(Additional Testing)	Composite	70% eff	30% eff	.21	.004	.09	.002

TABLE XXXVI - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
High-Speed Torquemeter	.28 1.21	.011 .046	Operate at a spectrum of torque levels	Particular	Hi-speed mech. torque-meter (1/5 of T55)	Did not have hi-speed torque-meter	1.10	.045	-	-
			(Additional Testing)	Composite	70% eff	30% eff	.18	.008	.10	.003
Cases, Bosses, Fittings	.25 .47	.011 .017	Utilize realistic external shafting arrangements, misalignments, and aircraft vibration during testing	Particular	T58 Rates		1.32	.060	-	-
			(Additional Testing)	Composite	70% eff	40% eff	.33	.012	.10	.004
Bearing Cage Wear, Cracking	.24 .50	.010 .018	Utilize production starting and include maintenance environment	Particular	T64 #2 Brng.		.50	.020	-	-
			(Additional Testing)	Composite	40% eff	20% eff	.10	.004	.05	.002
Fuel Control Failure	.20 2.58	.003 .058	Greater emphasis on using contaminated fuel, operating media (hydraulic or pneumatic), and operational cycling	Particular	T63 Rates 70% eff		5.80	.126	-	-
			(Additional Testing)	Composite	Pneumatic	Hyd/ Mech	1.80	.041	.04	.001

TABLE XXXVI - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	$\frac{.15}{5.09}$	$\frac{.009}{.305}$	Expose test engines to realistic maintenance (Additional Testing)	Composite	60% eff	30% eff	3.03	.20	1.51	.10
Turbine Support Structure and Fittings	$\frac{.15}{.54}$	$\frac{.007}{.025}$	Utilize realistic maintenance procedures during testing (Additional Testing)	Particular	T58 Rates		2.08	.140	-	-
				Composite	90% eff	40% eff	.13	.006	.06	.003
Cases, Secondary Structure Cracking	$\frac{.15}{.45}$	$\frac{.006}{.017}$	Use realistic shafting, realistic maintenance procedures, and aircraft vibration during testing (Additional Testing)	Particular	T58 Rates	—	6.50	.06	-	-
				Composite	90% eff	50% eff	.42	.016	.07	.003
Combustion Housing Corrosion, Fittings	$\frac{.15}{.58}$	$\frac{.005}{.020}$	Get more realistic use of aircraft vibratory stresses and maintenance procedures (Additional Testing)	Particular	T58 Rates	—	3.77	.130	-	-
				Composite	60% eff	30% eff	.35	.012	.05	.002
Foreign-Object Damage	$\frac{.14}{6.71}$	$\frac{.007}{.388}$	Utilize production design inlet protection during testing (Additional Testing)	Composite	60% eff	20% eff	.08	.004	.03	.001

TABLE XXXVI - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UEP			Maximum	Minimum	Index	UER	Index	UER
Bearing, Race Rotation Displacement	.13/.61	.007/.032	Intensify analysis of thermal gradients and dimensional control during testing or use of production variability with extended duration	Particular	T55 #2 Brng.		3.00	.150	-	-
			(Additional Testing)	Composite	80% eff	30% eff	.48	.025	.18	.010
			Specify positive retention of bearing outer races	Particular	T55 #2 Brng.		3.00	.150	.20	.010
			(Control of Designs)	Composite	100% eff		.61	.032	.61	.032
Lubrication Pump Failures	.11/.60	.003/.017	No corrective action							
Bearing Roller Skidding	.06/.30	.002/.013	Cycle anti-icing system during tests and measure thermal effects during testing	Particular	T64 Rates		2.10	.070	-	-
			(Additional Testing)	Composite	90% eff	20% eff	.05	.002	.01	-
			Utilize elliptical outer race bearings	Particular	T64		2.10	.070	-	-
			(Control of Designs)	Composite	100% eff	80% eff	.30	.013	.24	.011

TABLE XXXVII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: DESIGN EXECUTION
FACTOR ELEMENT: INADEQUATE TECHNOLOGY

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Carbon Seal Leakage	.84 / 3.28	.050 / .189	Positive contact seals (carbon) must be further developed to operate at 300-400 ft/sec running speeds with high reliability (Improved Technology)	Composite	80% eff	40% eff	2.62	.151	1.31	.075
Compressor Blade/Disc Fatigue	.75 / 2.40	.002 / .006	Develop integral blade/wheel castings with consistent material properties (Improved Technology)	Composite	70% eff	30% eff	.53	.001	.22	.001
			Analytical procedures for prediction of wear, dampening characteristics, resonance, and effect of manufacturing variations (cast assembly) should be refined (Improved Technology)	Composite	50% eff	20% eff	.38	.001	.15	.000
Compressor Vane Erosion	.35 / 1.11	.009 / .028	Develop methods for predicting natural frequency and fatigue life with eroded/corroded vanes (Improved Technology)	Composite	80% eff	40% eff	.28	.007	.14	.004

TABLE XXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Turbine Blades/Wheels Cracking	.30 1.17	.001 .001	Develop techniques for predicting effects of wear, dampening and temperature cycling (Improved Technology)	Composite	50% eff	20% eff	.15	.001	.06	.000
Fuel Control Failures	.27 2.58	.003 .058	Analysis of filtration, temperature, and vibration on fuel control component reliability (Improved Technology)	Composite	50% eff	20% eff	.14	.002	.05	.001
			Assembly or component testing should include all operational/environmental factors (Improved Technology)	Composite	70% eff	30% eff	.19	.002	.08	.001
Turbine Nozzle Band Cracking	.21 .57	.006 .016	Refine predicting techniques for dealing with thermal stresses (Improved Technology)	Composite	50% eff	30% eff	.10	.003	.07	.002
			Test with production variations in tolerances (Improved Technology)	Composite	90% eff	60% eff	.19	.005	.13	.004

TABLE XXXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Bearing Roller Skidding	.20 / .30	.008 / .013	Refine methods for predicting cage slip and race damage (Improved Technology)	Composite	90% eff	80% eff	.18	.007	.12	.005
			Test with engine aircraft mounting arrangement and locked power turbine (Improved Technology)	Composite	90% eff	60% eff	.18	.007	.12	.005
			Development of air bearings (Improved Technology)	Composite	100% eff	100% eff	.30	.013	.30	.013
Bearing Spalling (Classical B_{10})	.20 / .42	.003 / .006	Refine methods for predicting cage slip and race damage (Improved Technology)	Composite	90% eff	60% eff	.18	.003	.12	.002
				Particular	90% eff	60% eff	3.15	.045	2.10	.030
			Development of air bearings (Improved Technology)	Composite	100% eff	100% eff	.42	.006	.42	.006

TABLE XXXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Case Corrosion	.19/.27	.009/.012	Develop corrosion-resistant base materials	Composite	50% eff	20% eff	.10	.005	.01	.002
			(Improved Technology)	Particular	50% eff	20% eff	.45	.02	.18	.008
			Testing in realistic environment and artifically leaking gaskets	Composite	90% eff	50% eff	.17	.008	.10	.001
			(Improved Technology)	Particular	90% eff	50% eff	.81	.026	.45	.02

TABLE XXXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Combustion Liner Cracking, Warping	.19 / .19	.007 / .007	Thermal gradient analysis of combustion liner should be improved (Improved Technology)	Composite	40% eff	10% eff	.08	.003	.02	.001
				Particular	T55/T64 Rates 40% eff	T55/T64 Rates 10% eff	.36	.012	.09	.003
			Develop materials to withstand higher temperatures (Improved Technology)	Composite	60% eff	30% eff	.11	.004	.06	.002
				Particular	T55/T64 Rates 60% eff	T55/T64 Rates 30% eff	.54	.018	.27	.009
			Use a spectrum of manufacturing/assembly tolerance variations and extend duration (Additional Testing)	Composite	90% eff	50% eff	.17	.006	.10	.003
				Particular	T55/T64 Rates 90% eff	T55/T64 Rates 50% eff	.81	.027	.45	.015
Operator Induced	.18 / 2.54	.009 / 1.22	Improve engine diagnostics program (Improved Technology)	Composite	80% eff	50% eff	.15	.007	.09	.004
			Test in aircraft with standard operating procedures (Additional Testing)	Composite	60% eff	30% eff	.10	.005	.06	.003

TABLE XXXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Exhaust	.16 / .55	.001 / .004	Develop methods for predicting stresses from thermal growth (Improved Technology)	Composite	50% eff	20% eff	.08	.001	.03	.000
			Test with complete exhaust system (Additional Testing)	Composite	90% eff	50% eff	.14	.001	.08	.001
Erosion	.15 / 2.90	.010 / .140	Refine method of analysis of base material erosion using various particle sizes and composition (Improved Technology)	Composite	60% eff	40% eff	.09	.006	.06	.004
Bearing Spalling (Nonclassical)	.13 / 1.86	.003 / .033	Direct additional research at internal dynamics, debris effects on surface life, lubrication flow patterns, and heat patterns (Additional Analysis)	Composite	70% eff	30% eff	.09	.002	.04	.001
			Development of air bearings (Improved Technology)	Composite			1.30	.020	.40	.005

TABLE XXXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Diffuser Cracking	.12 .28	.008 .022	Increase attention concerning thermal and vibrational effects while testing	Composite	90% eff	70% eff	.23	.018	.18	.014
			(Additional Testing)	Particular	90% eff	70% eff	1.72	.14	1.37	.11
Airframe Related	.11 .36	.008 .148	Analysis of the effects of output shaft alignment and balance must be intensified - Criteria need to be established. (Improved Technology)	Composite	70% eff	30% eff	.08	.006	.03	.002
			Additional flight testing on bench testing with aircraft shafting systems (Additional Testing)	Composite	90% eff	50% eff	.10	.007	.05	.004
Combustion Support Structure Cracking	.11 .19	.004 .007	Additional analysis of vibrational effects on internal structure must be developed	Composite	40% eff	10% eff	.08	.003	.02	.001
			(Improved Technology)	Particular	T55 Rates 40% eff	T55 Rates 10% eff	.54	.020	.14	.005
			Extend testing and include aircraft vibration	Composite	90% eff	50% eff	.17	.006	.10	.003
			(Additional Testing)	Particular	T55 Rates 90% eff		1.22	.045	-	-

TABLE XXXVII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Bearing Race Rotation Displacement	.10 / .61	.004 / .032	Develop methods for determining rotational loads, effects of bore tolerances, and axial clamp-up loads (Improved Technology)	Composite	90% eff	60% eff	.09	.004	.06	.002
			Development of air bearings (Improved Technology)	Composite	100% eff	100% eff	.61	.032	.61	.032
Power Train Reduction	.07 / .72	.001 / .013	No specific remedial action	-	-	-	-	-	-	-
Turbine Shaft Couplings	.7 / .23	.001 / .003	Intensified research into improved analysis for shaft dynamics (Improved Technology)	Composite	50% eff	30% eff	.04	.001	.02	.000
			Test with external output shaft dynamic loads (Additional Testing)	Composite	90% eff	50% eff	.06	.001	.03	.000
Electrical Ignition	.06 / .26	.002 / .005	Extend testing with aircraft vibration included (Additional Testing)	Composite	70% eff	30% eff	.09	.002	.04	.001

TABLE XXXVIII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: MANUFACTURING AND QUALITY CONTROL
FACTOR ELEMENT: OPTIMUM ASS'Y/Q.C. NOT UTILIZED

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	.25 / 5.09	.015 / .305	Improve quality control of assembly procedures (Additional Q.C. Effort)	Composite	50% eff	25% eff	.12	.007	.06	.003
Accessory	.14 / .91	.004 / .025	Improve quality control of assembly procedures (AGB onto gearbox) (Additional Q.C. Effort)	Composite	70% eff	40% eff	.09	.003	.06	.002
Carbon Seal Leakage	.10 / 3.28	.005 / .189	Improve quality control of assembly procedures (Seal into housing) (Additional Q.C. Effort)	Composite	50% eff	25% eff	.05	.002	.02	.001
Bearing Race Rotation Displacement	.06 / .61	.002 / .032	Improve quality control of assembly procedures (Snapping into slot) (Additional Q.C. Effort)	Composite	50% eff	25% eff	.03	.001	.02	.000

TABLE XXXVIII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Compressor Blade/Disc Fatigue	.34/2.40	.001/.006	Develop nondestructive quality control methods for determination of material properties (Improve Technology)	Composite	70% eff	30% eff	.24	.001	.10	.000
Compressor Liner Wearing Cracking	.01/.04	.001/.004	Develop any inspection method for measuring internal density for nonmetallic materials (Improve Technology)	Composite	90% eff	30% eff	.01	.001	.00	.000
				Particular	[illegible]-3 Rates 50% eff	-	.45	.045	-	-

TABLE XXXIX. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
USAL FACTOR: MANUFACTURING AND QUALITY CONTROL
FACTOR ELEMENT: FAILURE TO FOLLOW SPECIFICATIONS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Bearing Spalling (Nonclassical)	$\frac{.15}{1.86}$	$\frac{.003}{.033}$	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	90% eff	50% eff	.14	.003	.07	.001
Turbine Support Structure and Fittings	$\frac{.09}{.54}$	$\frac{.004}{024}$	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	90% eff	50% eff	.08	.004	.05	.002
Power Train Reduction	$\frac{.07}{.72}$	$\frac{.001}{.013}$	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	50% eff	25% eff	.04	.001	.02	.000
Carbon Seal Leakage	$\frac{.06}{3.28}$	$\frac{.004}{.169}$	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	90% eff	50% eff	.05	.004	.03	.002
Lubrication System Miscellaneous	$\frac{.06}{.20}$	$\frac{.002}{.006}$	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control	Composite	50% eff	25% eff	.03	.001	.01	.000

TABLE XXXIX - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Air Valve Binding Leaking	.04 .38	.001 .007	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	50% eff	25% eff	.02	.001	.01	.000
Accessory	.04 .91	.001 .025	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control	Composite	50% eff	25% eff	.02	.001	.01	.000
Combustion Housing Corrosion	.03 .58	.001 .020	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	50% eff	25% eff	.01	.001	.01	.000
Combustion Swirl Cup Problems	.03 .17	.001 .006	Additional quality control of detail material properties and manufacturing variations	Composite	90% eff	60% eff	.03	.001	.02	.001
			(Improve Quality Control)	Particular	90% eff	60% eff	1.35	.045	.90	.030
Cage Wear, Cracking	.03 .50	.001 .018	Additional quality control of detail material properties and manufacturing variations (Improve Quality Control)	Composite	50% eff	25% eff	.01	.001	.01	.000

TABLE XL. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: OPERATIONS AND MAINTENANCE
FACTOR ELEMENT: AVOIDABLE OPERATION OF ENGINE OUTSIDE LIMITS

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Operator Induced	$\frac{.95}{2.54}$	$\frac{.050}{.172}$	Enlist procedures to prevent hot starts, erroneous removals for low power, overstress or overtorque (Control of Operations)	Composite	60% eff	20% eff	.57	.030	.19	.010
Erosion	$\frac{.20}{2.90}$	$\frac{.010}{.140}$	Reduce operation of engine under severe dust/dirt conditions (Control of Operations)	Composite	50% eff	25% eff	.10	.005	.05	.02
Bearing Spalling (Nonclassical)	$\frac{.04}{1.86}$	$\frac{.001}{.033}$	Adhere to engine shutdown procedures (Control of Operations)	Composite	70% eff	30% eff	.03	.001	.01	.000
				Particular	70% eff	30% eff	1.68	.042	.72	.018

TABLE XLI. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: OPERATIONS & MAINTENANCE
FACTOR ELEMENT: MAINTENANCE CRITERIA FOR REMOVALS AND PROCEDURES ILL-DEFINED

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Environmental	.60 / 1.09	.030 / .059	Improve procedures and criteria for oil and fuel contamination analysis (Improved Maintenance)	Composite	70% eff	30% eff	.42	.021	.18	.009
Fuel Control Failures	.50 / 2.58	.007 / .058	Improve maintenance practices (reduce misadjustment, erroneous troubleshooting on fuel control) (Improved Maintenance)	Composite	50% eff	25% eff	.25	.04	.12	.002
Electrical Wiring & Thermocouples	.14 / .31	.003 / .006	Improve criteria for wiring damage & repair techniques (Improved Maintenance)	Composite	50% eff	25% eff	.07	.002	.03	.001
Cases Secondary Structure Cracking	.09 / .45	.004 / .017	More definitive manuals concerning drive train misalignments (Improved Maintenance)	Composite	70% eff	30% eff	.06	.003	.03	.001
Air Tubes, Fittings	.09 / .17	.002 / .003	Improve procedures for repair of air tubes and fittings (Improved Maintenance)	Composite	50% eff	25% eff	.05	.001	.02	.000
Turbine Shaft Coupling	.05 / .23	.001 / .003	Improved output shaft vibration level criteria (Improved Maintenance)	Composite	70% eff	30% eff	.04	.001	.02	.000

TABLE XLI - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Bearing Spalling (Nonclassical)	.04 / 1.86	.001 / .033	Define more realistic means cf turning rotors (Improved Maintenance)	Composite	90% eff	60% eff	.04	.001	.02	.001
Lubrication tubes	.03 / .22	.003 / .007	Improve procedures for repair of lubrication tubes and fittings (Improved Maintenance)	Composite	50% eff	25% eff	.02	.002	.01	.001

TABLE XLII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: OPERATIONS & MAINTENANCE
FACTOR ELEMENT: MAINTENANCE DAMAGE

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Improper Maintenance	3.06/5.09	.200/.305	Concentrate attention on proper maintenance and inspection practices (Improved Maintenance)	Composite	60% eff	10% eff	1.84	.120	.31	.020
Airframe Related	.84/2.36	.045/.148	Utilize existing accessibility and perform on-aircraft maintenance whenever possible (Improved Maintenance)	Composite	70% eff	30% eff	.59	.032	.25	.013
Foreign-Object Damage	.40/6.71	.022/.388	Take additional care in performing maintenance in engine area to check for tools, hardware, etc. (Improved Maintenance)	Composite	80% eff	40% eff	.32	.018	.16	.009
High-Speed Torquemeter	.24/1.21	.009/.046	Critical assembly techniques must be emphasized in procedures	Composite	[illegible]0% eff	20% eff	.19	.007	.05	.002
			(Improved Maintenance)	Particular	80% eff	20% eff	.96	.032	.24	.008
Compressor Vane Erosion	.22	.007	Improve compressor maintenance (water-wash and corrosion prevention treatment) (Improved Maintenance)	Composite	80% eff	20% eff	.17	.006	.05	.001

TABLE XLII - Continued

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Electrical Wiring and Thermocouples	$\frac{.14}{.31}$	$\frac{.003}{.006}$	Concentrate attention on proper maintenance and inspection practices (Improved Maintenance)	Composite	50% eff	10% eff	.02	.002	.01	.000
Bearing Spalling (Nonclassical)	$\frac{.12}{1.86}$	$\frac{.001}{.033}$	Prevent reinstallation of used swollen O-rings and using a wrench on bearing retaining bolt (Improved Maintenance)	Composite	70% eff	30% eff	.08	.001	.04	.000
Environmental	$\frac{.10}{1.09}$	$\frac{.007}{.059}$	Concentrate attention on proper maintenance and inspection practices (Improved Maintenance)	Composite	60% eff	10% eff	.06	.004	.01	.001
Cases, Bosses, Fittings	$\frac{.08}{.47}$	$\frac{.005}{.021}$	Prevent practice of using a wrench on the wrong size bolt (Improved Maintenance)	Composite	60% eff	10% eff	.05	.003	.01	.001
Turbine Support Structure	$\frac{.06}{.54}$	$\frac{.004}{.025}$	Adhere to double wrenching of fittings and mounting nuts where required (Improved Maintenance)	Composite	50% eff	25% eff	.03	.002	.01	.001
Lubrication Tubes, Fittings	$\frac{.04}{.22}$	$\frac{.004}{.007}$	Improve removal procedures and reduce possible chafing of lines (Improved Maintenance)	Composite	40% eff	10% eff	.02	.002	.00	.000

TABLE XLIII. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: OPERATIONS & MAINTENANCE
FACTOR ELEMENT: OPTIMUM LOGISTICS MANAGEMENT PROGRAM NOT UTILIZED

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Convenience	4.36 / 5.46	.400 / .495	Improve logistics management programs	Particular			13.20	1.200		
				Composite	80% eff	-	2.20	.200	2.20	.200

TABLE XLIV. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: OPERATIONS & MAINTENANCE
FACTOR ELEMENT: INADEQUATE DIAGNOSTICS TECHNOLOGY

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Convenience	.55 / 5.46	.045 / .495	Improve prognostics to detect failures	Composite	60% eff	20% eff	.33	.027	.11	.009
Improper Maintenance	.38 / 5.09	.014 / .305	Improve diagnostics program	Composite	40% eff	20% eff	.15	.050	.07	.020
Fuel Control Failures	.36 / 2.58	.005 / .058	Improve diagnostics program	Composite	70% eff	30% eff	.25	.004	.11	.001
Operator Induced	.25 / 2.54	.010 / .022	Improve diagnostics program	Composite	50% eff	25% eff	.12	.005	.06	.002
Erosion	.39 / 2.90	.004 / .140	Improve diag- -tics program	Composite	80% eff	20% eff	.07	.003	.02	.001
Turbine Shaft Coupling	.05 / .23	.001 / .003	Improve diagnostics program	Composite	60% eff	20% eff	.03	.001	.02	.000

TABLE XLV. IDENTIFICATION & QUANTIFICATION OF REMEDIAL ACTIONS
CAUSAL FACTOR: OPERATIONS AND MAINTENANCE
FACTOR ELEMENT: CANNOT BE ALTERED OR ADDRESSED

Failure Mode	Composite		Potential Remedial Action	Engine Baseline	Assumptions		Maximum		Minimum	
	Index	UER			Maximum	Minimum	Index	UER	Index	UER
Foreign-Object Damage	.61 6.71	.036 .388	No remedial action	-	-	-	-	-	-	-
Convenience	.55 5.46	.044 .495	No remedial action	-	-	-	-	-	-	-
Operator Induced	.45 2.54	.019 .122	No remedial action	-	-	-	-	-	-	-
Improper Maintenance	.38 5.09	.014 .305	No remedial action	-	-	-	-	-	-	-
Airframe Related	.10 2.36	.014 .148	No remedial action	-	-	-	-	-	-	-
Environmental	.17 1.09	.010 .059	No remedial action	-	-	-	-	-	-	-

APPENDIX II

SUMMARIZATION OF REMEDIAL ACTIONS

TABLE XLVI. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: TESTING
SUBGROUP: BASIC TEST CONFIGURATION/TYPE

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Additional Flight Testing and Bench Testing With Production Accessories (Shafting)	Airframe Related	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.60	.100	-	-
		- Inadequate technology	Composite	.58	.036	.24	.16
	PARTICULAR SUBTOTAL			1.60	.100	-	-
	COMPOSITE SUBTOTAL			.58	.036	.24	.016
(A) Use of Production Variability of Bearing Housings, Realistic Cycling and Additional Duration. (B) Use of Production Oil Systems in Realistic Heat Scavenge (C) Use of Production Variability on Splines & Realistic Temperature	Bearing Spalling (Nonclassical)	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	2.12	.038	-	-
			Composite	.49	.008	.14	.002
	PARTICULAR SUBTOTAL			2.12	.038	-	-
	COMPOSITE SUBTOTAL			.49	.008	.14	.002
Use Realistic Maintenance On Aircraft Mounting Installation	Fuel Control Failures	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.42	.013	.24	.007
	COMPOSITE SUBTOTAL			.42	.013	.24	.007

TABLE XLVI - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Utilize Realistic External Shafting Arrangements, Misalignments, and Airframe Vibration during Testing	Cases Secondary Structure Cracking	Design Execution - Analysis available, not used, not cost effective	Particular	1.50	.060	-	-
			Composite	.33	.012	.10	.004
	Combustion Housing and Pitting Corrosion	Design Execution - Analysis available, not used, not cost effective	Particular	1.50	.060	-	-
			Composite	.42	.016	.07	.003
	Cases, Bosses, Fittings	Design Execution - Analysis available, not used, not cost effective	Particular	3.77	.130	-	-
			Composite	.35	.012	.05	.002
	PARTICULAR SUBTOTAL			6.77	.250	-	-
	COMPOSITE SUBTOTAL			1.10	.040	.22	.009
Utilize Complete Engine Protection During Testing	Foreign-Object Damage	Design Execution - Analysis available, not used, not cost effective - Analysis available, not used, reasonable cost & effectiveness					
	COMPOSITE SUBTOTAL		Composite	.26	.015	.13	.007
Include Thermal and Vibrational Effects While Testing	Diffuser Cracking	Design Execution - Inadequate technology	Particular	1.72	.140	1.37	.110
			Composite	.23	.018	.18	.014
	PARTICULAR SUBTOTAL			1.72	.140	1.37	.110
	COMPOSITE SUBTOTAL			.23	.018	.18	.014

TABLE XLVI - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Perform Tests With Normal Operator Techniques (Emphasis on Flight Testing)	Operator Induced	Design Execution - Analysis available, not used, reasonable cost & effectiveness - Inadequate technology	Composite	.22	.012	.12	.006
	COMPOSITE SUBTOTAL			.22	.012	.12	.006
Test With Engine Aircraft Mounting Arrangement and Locked Power Turbine	Bearing Roller Skidding	Design Execution - Inadequate technology	Composite	.18	.007	.12	.005
	COMPOSITE SUBTOTAL			.18	.007	.12	.005
Utilize Aircraft Output Shafting During Testing	Turbine Shaft Coupling	Design Execution - Analysis available, not used, reasonble cost, reasonable effectiveness - Inadequate technology	Composite	.24	.004	.15	.001
	COMPOSITE SUBTOTAL			.24	.004	.15	.001
Extend Duration of Test and Include Aircraft Vibration	Combustion Support Cracking	Design Execution - Inadequate technology	Particular Composite	1.22 .17	.04[illegible] .006	- .10	- .003
	Electrical Ignition	Design Execution - Inadequate technology	Composite	.09	.002	.04	.001

TABLE XLVI - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
	Exhaust	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.02	.001	.01	-
	PARTICULAR SUBTOTAL			1.2[illegible]	.045	-	-
	COMPOSITE SUBTOTAL			.28	.009	.15	.004
Extend Length of Test With Entire Aircraft Lube System Included	Lubrication Pump Failures	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.80	.06	.90	.03
			Composite	.15	.005	.90	.03
	PARTICULAR SUBTOTAL			1.80	.06	.90	.03
	COMPOSITE SUBTOTAL			.15	.005	.90	.03
Test With Complete Exhaust System	Exhaust	Design Execution - Inadequate technology	Composite	.14	.001	.08	.001
	COMPOSITE SUBTOTAL			.14	.001	.08	.001
Test With External Shafting & Aircraft Vibration (Flight Tests)	Turbine Support Structure	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.07	.004	.03	.002

TABLE XLVI - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
	Cases, Secondary Structure Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.50	.060	-	-
			Composite	.06	.002	.03	.001
	PARTICULAR SUBTOTAL			1.50	.060	-	-
	COMPOSITE SUBTOTAL			.13	.006	.06	.003
Test Using Production Manufacturing Techniques and Realistic Vibration; Maintenance Environment Should Also Be Maintained	Combustion Housing Corrosion & Fittings	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	3.30	.11	-	-
			Composite	.06	.002	.03	.001
	PARTICULAR SUBTOTAL			3.30	.11	-	-
	COMPOSITE SUBTOTAL			.06	.002	.03	.001
TOTAL (SUBGROUP)	PARTICULAR			21.49	.855	3.11	.167
	COMPOSITE			4.48	.176	2.76	.106

TABLE XLVII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: TESTING
SUBGROUP: TEST EXECUTION - CYCLING, ENVIRONMENT, TORQUE/TEMP. CYCLING

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Use Contaminated Airflow, Realistic Maintenance Procedures and Extended Duration	Carbon Seal Leakage	Design Execution - Analysis available, not used, not cost effective	Particular	3.40	.200	-	-
			Composite	.54	.030	.18	.010
	PARTICULAR SUBTOTAL			3.40	.200	-	-
	COMPOSITE SUBTOTAL			.54	.030	.18	.010
Use Contaminated Ambient Air During Testing	Air Valve Binding Leaking	Design Execution - Analysis available, not used, not cost effective	Particular	.42	.010	-	-
			Composite	.21	.004	.09	.002
	PARTICULAR SUBTOTAL			.42	.010	-	-
	COMPOSITE SUBTOTAL			.21	.004	.09	.002
Operate at a Spectrum of Torque Levels	High-Speed Torquemeter	Design Execution - Analysis available, not used, not cost effective	Particular	1.10	.040	-	-
			Composite	.18	.008	.10	.003
	PARTICULAR SUBTOTAL			1.10	.040	-	-
	COMPOSITE SUBTOTAL			.18	.008	.10	.003
Test With Realistic Environment Including Artificially Leaking Gaskets	Case Corrosion	Design Execution - Inadequate technology	Particular	.81	.036	.45	.020
			Composite	.17	.008	.10	.004
	PARTICULAR SUBTOTAL			.81	.036	.45	.020
	COMPOSITE SUBTOTAL			.17	.008	.10	.004

TABLE XLVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Expose Test Engines to Realistic Maintenance During Testing	Improper Maintenance	Design Execution - Analysis available, not used, not cost effective - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	3.09	.204	.155	.102
	Tubing Support Structure	Design Execution - Analysis available, not used, not cost effective	Particular	2.80	.140	-	-
			Composite	.13	.006	.06	.003
	PARTICULAR SUBTOTAL			5.89	.344	.155	.102
	COMPOSITE SUBTOTAL			3.22	.210	.215	.105
Increase Emphasis on Reducing Contaminated Fuel and Operating Media (Hydraulic or Pneumatic), Include Operational Cycling in the Testing	Fuel Control Failure	Design Execution - Analysis available, not used, not cost effective - Inadequate technology	Particular	5.80	.126	-	-
			Composite	1.99	.062	.12	.002
	PARTICULAR SUBTOTAL			5.80	.126	-	-
	COMPOSITE SUBTOTAL			1.99	.062	.12	.002
Test for Fatigue Strength After Erosion Test	Compressor Vane Erosion	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	6.40	.16	-	-
			Composite	.72	.020	.56	.014
	PARTICULAR SUBTOTAL			6.40	.16	-	-
	COMPOSITE SUBTOTAL			.72	.020	.56	.014

TABLE XLVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Engine Baseline	Potential Benefit: Maximum Index	Maximum UER	Minimum Index	Minimum UER
Utilize Anti-Icing Feature and Complete Cycling During Testing	Bearing Cage Wear, Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.12	.003	.06	.001
	Bearing Roller Skidding	Design Execution - Analysis available, not used, not cost effective	Particular	.15	.090	-	-
			Composite	.05	.002	.01	.000
	PARTICULAR SUBTOTAL			.15	.090	-	-
	COMPOSITE SUBTOTAL			.17	.093	.07	.001
Maintenance and Vibrational Effects Should Be Considered More Intensely in the Testing of the Engine	Lubrication Filters, Coolers	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.30	.020	-	-
			Composite	.11	.002	.06	.001
	PARTICULAR SUBTOTAL			1.30	.020	-	-
	COMPOSITE SUBTOTAL			.11	.002	.06	.001
Utilize Production Starting and Maintenance Environment During Testing	Bearing Case Wear, Cracking	Design Execution - Analysis available, not used, not cost effective	Particular	.50	.020	-	-
			Composite	.10	.004	.05	.002
	PARTICULAR SUBTOTAL			.5C	.020	-	-
	COMPOSITE SUBTOTAL			.10	.004	.05	.002
TOTAL (SUBGROUP)	PARTICULAR			25.89	1.049	.660	.123
	COMPOSITE			7.41	.354	1.55	.144

TABLE XLVIII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: TESTING
SUBGROUP: ADDITIONAL DURATION

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Extend Duration of Testing	Bearing Spalling (Nonclassical)	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	24.41	.472	.57	.010
		- Inadequate technology	Composite	1.67	.030	.74	.013
	High-Speed Torquemeter	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.10	.04	-	-
			Composite	.14	.006	.06	.003
	Diffuser Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.03	.002	.02	.001
	Accessory	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.43	.012	.22	.006
	Power Train Reduction	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.14	.002	.02	.001
	PARTICULAR SUBTOTAL			25.51	.512	.57	.010
	COMPOSITE SUBTOTAL			2.41	.052	1.06	.024
TOTAL (SUBGROUP)	PARTICULAR			26.11	.528	.83	.018
	COMPOSITE			2.41	.052	1.06	.024

TABLE XLIX. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: TESTING
SUBGROUP: SPECIMEN VARIABILITY

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Test With a Spectrum of Parts With Production Variations	Compressor Blade/Disc Fatigue	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	1.44	.004	1.20	.003
	COMPOSITE SUBTOTAL			1.44	.004	1.20	.003
Investigate Accelerated Aging Test and Speed Resonance Search During Test as Well as Include Manufacturing Variations	Turbine Blade/Wheel Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.70	.001	.47	.000
	COMPOSITE SUBTOTAL			.70	.001	.47	.000
Intensify Analysis of Thermal Gradients and Dimensional Control During Testing or Use More Production Variability	Bearing Race Rotation Displacement	Design Execution - Analysis available, not used not cost effective	Particular	3.00	.150	-	-
			Composite	.48	.025	.18	.010
	PARTICULAR SUBTOTAL			3.00	.150	-	-
	COMPOSITE SUBTOTAL			.48	.025	.18	.010
Test With Production Variations in Tolerances	Turbine Nozzle Band Cracking	Design Execution - Inadequate technology	Composite	.19	.005	.13	.004
	COMPOSITE SUBTOTAL			.19	.005	.13	.004
Test With a Variety if Reinstalled Seals at Varying Speeds Including the Complete Lube System	Carbon Seal Leakage	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	10.20	.600	-	-
			Composite	.18	.010	.08	.005
	PARTICULAR SUBTOTAL			10.20	.600	-	-
	COMPOSITE SUBTOTAL			.18	.010	.08	.005

TABLE XLIX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Test Using a Spectrum of Manufacturing/Assembly Tolerance Variations	Combustion Liner Cracking Warping	Design Execution - Inadequate technology	Particular	.81	.027	.45	.015
			Composite	.17	.006	.10	.003
	PARTICULAR SUBTOTAL			.81	.027	.45	.015
	COMPOSITE SUBTOTAL			.17	.006	.10	.003
Test With Extremes in Variability	Combustion Swirl Cup Problems	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.40	.05	-	-
			Composite	.09	.003	.05	.002
	PARTICULAR SUBTOTAL			1.40	.05	-	-
	COMPOSITE SUBTOTAL			.09	.003	.05	.002
TOTAL (SUBGROUP)	PARTICULAR			17.73	.837	2.25	.022
	COMPOSITE			3.25	.054	2.21	.027
TOTAL (GROUP)	PARTICULAR			91.22	3.269	6.85	.330
	COMPOSITE			17.55	.636	7.53	.301

TABLE L. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED TECHNOLOGY
SUBGROUP: DEVELOPMENT OF NEW MATERIALS/DESIGNS

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Development of Air Bearings	Bearing Spalling (Nonclassical)	Not Applicable	Composite	1.30	.020	.40	.005
	Bearing Spalling (Classical)	Not Applicable	Composite	.42	.006	.42	.006
	Bearing Race Rotation Displacement	Not Applicable	Composite	.61	.032	.61	.032
	Cage Wear and Cracking, Warping	Not Applicable	Composite	.50	.018	.50	.018
	Bearing Roller Skidding	Not Applicable	Composite	.30	.013	.30	.013
	COMPOSITE SUBTOTAL			3.13	.089	2.23	.074
Develop Positive Contact Seals (Carbon) To Operate at 300-400 Ft/Sec Running Speeds With High Reliability	Carbon Seal Leakage	Design Execution - Inadequate technology	Composite	2.62	.151	1.31	.075
	COMPOSITE SUBTOTAL			2.62	.151	1.31	.075
Develop Corrosion-Resistant Base Materials	Case Corrosion	Design Execution - Inadequate technology	Particular	.45	.020	.18	.008
			Composite	.10	.005	.04	.002
	PARTICULAR SUBTOTAL			.45	.020	.18	.008
	COMPOSITE SUBTOTAL			.10	.005	.04	.002

TABLE L - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Develop Integral Castings With Consistent Material Properties	Compressor Blade/Disc	Design Execution - Inadequate technology	Composite	.53	.001	.22	.001
	COMPOSITE SUBTOTAL			.53	.001	.22	.001
Develop Materials To Withstand Higher Temperatures	Combustion Liner Cracking, Warping	Design Execution - Inadequate technology	Particular	.54	.018	.27	.009
			Composite	.11	.004	.06	.002
	PARTICULAR SUBTOTAL			.54	.018	.27	.009
	COMPOSITE SUBTOTAL			.11	.004	.06	.002
TOTAL (SUBGROUP)	PARTICULAR			7.27	.279	4.21	.167
	COMPOSITE			6.49	.250	3.86	.154

TABLE LI. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED TECHNOLOGY
SUBGROUP: EFFECT OF NORMAL OPERATIONS

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Refine Methods for Predicting Cage Slip and Race Damage	Bearing Roller Skidding	Design Execution - Inadequate technology	Composite	.18	.007	.12	.005
	Bearing Spalling (Classical)	Design Execution - Inadequate technology	Particular	3.15	.045	2.10	.030
			Composite	.18	.003	.12	.002
	PARTICULAR SUBTOTAL			3.15	.045	2.10	.030
	COMPOSITE SUBTOTAL			.36	.010	.24	.007
Analyze the Effect of Filtration, Temperature, and Vibration on Fuel Control Component Reliability	Fuel Control Failures	Design Execution - Inadequate technology	Composite	.14	.002	.05	.001
	COMPOSITE SUBTOTAL			.14	.002	.05	.001
Refine Prediction Technique for Investigation of Thermal Stresses	Turbine Nozzle Band Cracking	Design Execution - Inadequate technology	Composite	.10	.003	.07	.002
	COMPOSITE SUBTOTAL			.10	.003	.07	.002
Direct Additional Research Into the Areas of Internal Dynamics, Debris Effects on Surface Life, Lubrication Flow and Heat Patterns	Bearing Spalling (Nonclassical)	Design Execution - Inadequate technology	Composite	.09	.002	.04	.001
	COMPOSITE SUBTOTAL			.09	.002	.04	.001

TABLE 11 - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Analysis of Combustion Liner Thermal Gradients Should Be Advanced	Combustion Liner Cracked Warping	Design Execution - Inadequate technology	Particular	.36	.012	.09	.003
			Composite	.08	.012	.09	.003
	PARTICULAR SUBTOTAL			.36	.012	.09	.003
	COMPOSITE SUBTOTAL			.08	.003	.02	.001
Analyze Vibrational Effects More Intensely	Combustion Support Cracking	Design Execution - Inadequate technology	Particular	.54	.020	.14	.005
			Composite	.08	.003	.02	.001
	PARTICULAR SUBTOTAL			.54	.020	.14	.005
	COMPOSITE SUBTOTAL			.08	.003	.02	.001
Develop Better Methods for Predicting Stresses From Thermal Growth	Exhaust	Design Execution - Inadequate technology	Composite	.08	.001	.03	.000
	COMPOSITE SUBTOTAL			.08	.001	.03	.000
Analyze Shaft Dynamics With Increased Loads	Turbine Shaft Coupling	Design Execution - Inadequate technology	Composite	.04	.001	.02	.000
	COMPOSITE SUBTOTAL			.04	.001	.02	.000
TOTAL (SUBGROUP)	PARTICULAR			4.68	.093	2.66	.047
	COMPOSITE			.97	.025	.49	.013

TABLE LII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED TECHNOLOGY
SUBGROUP: EFFECTS OF DEGRADED CONDITIONS OR VARIATION IN NORMAL CONDITIONS

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Refine Analytical Procedures Pertaining to Prediction of Wear Dampening Characteristics, Resonance, and Manufacturing Variation	Compressor Blade/Disc Fatigue	Design Execution - Inadequate technology	Composite	.53	.001	.22	.001
	COMPOSITE SUBTOTAL			.53	.001	.22	.001
Improve Methods for Predicting Natural Frequency and Fatigue Life With Eroded/Corroded Vanes	Compressor Vane Erosion	Design Execution - Inadequate technology	Composite	.28	.007	.14	.004
	COMPOSITE SUBTOTAL			.28	.007	.14	.004
Develop Techniques for Predicting Load Effects of Wear on Dampening and Temperature Cycling	Turbine Blade/Wheels Cracking	Design Execution - Inadequate technology	Composite	.15	.001	.06	.000
	COMPOSITE SUBTOTAL			.15	.001	.06	.000
Increased Analysis of Base Material Using Various Particle Sizes and Compositions	Erosion	Design Execution - Inadequate technology	Composite	.09	.006	.06	.004
	COMPOSITE SUBTOTAL			.09	.006	.06	.004
Develop Methods for Determining Rotational Loads, Effects of Bore Tolerances, and Axial Clamp of Loads	Bearing Race Rotation, Displacement	Design Execution - Inadequate technology	Composite	.09	.004	.06	.002
	COMPOSITE SUBTOTAL			.09	.004	.06	.002

TABLE LII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Analyze the Effects of Output Shaft Alignment	Airframe Related	Design Execution - Inadequate technology	Composite	.08	.006	.03	.002
	COMPOSITE SUBTOTAL			.08	.006	.03	.002
TOTAL (SUBGROUP)	PARTICULAR			1.22	.025	.57	.013
	COMPOSITE			1.22	.025	.57	.013

TABLE LIII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED TECHNOLOGY
SUBGROUP: IMPROVED DIAGNOSTICS TECHNOLOGY

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Develop Prognostics to Detect Failures	Convenience	Operations & Maintenance - Inadequate diagnostics technology	Composite	.33	.027	.11	.009
	COMPOSITE SUBTOTAL			.33	.027	.11	.009
Improve Diagnostics Program To More Accurately Troubleshoot Problems, Isolate Faults, and Reduce Erroneous Removals	Improper Maintenance	Operations & Maintenance - Inadequate diagnostics technology	Composite	.15	.050	.07	.020
	Fuel Control Failure	Operations & Maintenance - Inadequate diagnostics technology	Composite	.25	.004	.11	.001
	Erosion	Operations & Maintenance - Inadequate diagnostics technology	Composite	.07	.003	.02	.001
	Turbine Shaft Coupling	Operations & Maintenance - Inadequate diagnostics technology	Composite	.03	.001	.02	.000
	Operator Induced	Design Execution - Inadequate technology - Inadequate diagnostics technology	Composite	.27	.012	.15	.006
	COMPOSITE SUBTOTAL			.77	.070	.37	.028
TOTAL (SUBGROUP)	PARTICULAR			1.10	.097	.48	.037
	COMPOSITE			1.10	.097	.48	.037

TABLE LIV. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED TECHNOLOGY
SUBGROUP: QUALITY CONTROL

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Develop Nondestruct Quality Control Methods for Determination of Material Properties	Compressor Blade/Disc Fatigue	Manufacturing & Quality Control - Alternate assembly/quality control procedure available	Composite	.24	.001	.10	.000
	COMPOSITE SUBTOTAL			.24	.001	.10	.000
Develop a Manufacturing Method for Measuring Internal Density of Compressor Lining	Compressor Liner Wearing, Cracking	Manufacturing & Quality Control - Alternate assembly/quality control procedure not available	Particular	.45	.045	-	-
			Composite	.01	.001	.00	.000
	PARTICULAR SUBTOTAL			.45	.045	-	-
	COMPOSITE SUBTOTAL			.01	.001	.00	.000
TOTAL (SUBGROUP)	PARTICULAR			.69	.046	.10	.000
	COMPOSITE			.25	.002	.10	.000
TOTAL (GROUP)	PARTICULAR			14.96	.540	8.02	.264
	COMPOSITE			10.03	.299	5.899	.217

TABLE LV. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: DE-EMPHASIS ON PERFORMANCE/WEIGHT IN REQUIREMENTS
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Utilize Axial/Centrifugal Over Axial Flow Compressor	Foreign-Object Damage	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis Preliminary Design - Design concept	Particular	25.94	1.50	5.19	.300
			Composite	4.05	.238	4.05	.238
	Erosion	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis	Particular	161.46	7.80	.83	.04
			Composite	1.53	.090	1.53	.090
	Compressor Vane Erosion	Specifications & Requirements - Performance/weight emphasis	Particular	9.91	.250	2.80	.070
			Composite	.50	.013	.50	.013
	PARTICULAR SUBTOTAL			197.31	9.550	8.82	.410
	COMPOSITE SUBTOTAL			6.08	.341	6.08	.341
Adequate Low-Cycle Fatigue	Turbine Blade Wheel Cracking	Specifications & Requirements - Performance/weight emphasis	Particular	.50	.001	.30	.000
			Composite	.40	.001	.40	.001
	PARTICULAR SUBTOTAL			.50	.001	.30	.000
	COMPOSITE SUBTOTAL			.40	.001	.40	.001

TABLE LV - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Specify Labyrinth Seals	Carbon Seal Leakage	Specifications & Requirements - Performance/weight emphasis	Particular	12.98	.750	.87	.050
		Preliminary Design - Design concept	Composite	3.19	.183	3.19	.183
	PARTICULAR SUBTOTAL			12.98	.750	.87	.050
	COMPOSITE SUBTOTAL			3.19	.183	3.19	.183
TOTAL	PARTICULAR			428.38	21.501	17.17	.840
	COMPOSITE			14.74	.823	14.74	.823

TABLE LVI. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: REQUIREMENT FOR SPECIFIC FEATURES
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Require Installation of Engine Inlet Screens	Foreign-Object Damage	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis	Particular	34.59	2.000	2.59	.150
			Composite	2.35	.138	2.35	.138
	PARTICULAR SUBTOTAL			34.59	2.000	2.59	.150
	COMPOSITE SUBTOTAL			2.35	.138	2.35	.138
Require Installation of Inlet Particle Separator	Foreign-Object Damage	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis	Particular	29.45	1.700	.86	.050
			Composite	2.04	.120	2.04	.120
	Erosion	Specifications & Requirements - Lack of requirement for features - Performance/weight emphasis	Particular	155.55	7.500	3.73	.18
			Composite	.68	.040	.68	.040
	PARTICULAR SUBTOTAL			185.00	9.200	4.59	.230
	COMPOSITE SUBTOTAL			2.72	.160	2.72	.160
TOTAL	PARTICULAR			219.59	11.200	7.18	.380
	COMPOSITE			5.07	.298	5.07	.298

TABLE LVII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED MAINTENANCE
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Improve Procedures & Criteria for Oil and Fuel Contamination Analysis	Environmental	Operations & Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.42	.021	.18	.009
	COMPOSITE SUBTOTAL			.42	.021	.18	.009
Improve Maintenance Practices (Reduce Misadjustment, Erroneous Troubleshooting on Fuel Control)	Fuel Control Failures	Operations and Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.25	.004	.12	.002
	COMPOSITE SUBTOTAL			.25	.004	.12	.002
Improve Criteria for Wiring Damage & Repair Techniques	Electrical Wiring & Thermocouples	Operations and Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.07	.002	.03	.001
	COMPOSITE SUBTOTAL			.07	.002	.03	.001
Define More Realistic Means of Turning Rotor	Bearing Spalling (Nonclassical)	Operations and Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.04	.001	.02	.001
	COMPOSITE SUBTOTAL			.04	.001	.02	.001

TABLE LVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Improved Output Shaft Vibration Level Criteria	Turbine Shaft Coupling	Operations & Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.04	.001	.02	.000
	COMPOSITE SUBTOTAL			.04	.001	.02	.000
Manuals Concerning Drive Train Misalignments Must Be Written More Clearly	Cases, Secondary Structure	Operations & Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.06	.003	.03	.001
	COMPOSITE SUBTOTAL			.06	.003	.03	.001
Improve Procedures for Repair of Air Tubes, Fittings	Air Tubes, Fittings	Operations & Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.05	.001	.02	.000
	COMPOSITE SUBTOTAL			.05	.001	.02	.000
Improve Procedures for Repair of Lubrication Tubes, Fittings	Lubrication Tubes, Fittings	Operations & Maintenance - Maintenance criteria for removal and procedures ill-defined	Composite	.02	.002	.01	.001
	COMPOSITE SUBTOTAL			.02	.002	.01	.001

TABLE LVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Greater Attention to Proper Maintenance and Inspection Practices	Improper Maintenance	Operations & Maintenance - Maintenance damage	Composite	1.84	.120	.31	.020
	Foreign-Object Damage	Operations & Maintenance - Maintenance damage	Composite	.32	.018	.16	.009
	Airframe Related	Operations & Maintenance - Maintenance damage	Composite	.59	.032	.25	.013
	Environmental	Operations & Maintenance - Maintenance damage	Composite	.06	.004	.01	.001
	Electrical Wiring and Thermocouples	Operations & Maintenance - Maintenance damage	Composite	.02	.002	.01	.000
	High-Speed Torquemeter	Operations & Maintenance - Maintenance damage	Composite	.19	.067	.05	.002
	Compressor Vane Erosion	Operations & Maintenance - Maintenance damage	Composite	.17	.006	.05	.001
	Bearing Spalling (Nonclassical)	Operations & Maintenance - Maintenance damage	Composite	.08	.001	.04	.000
	Cases, Boxes, Fittings	Operations & Maintenance - Maintenance damage	Composite	.05	.003	.01	.001
	Lubrication Tubes, Fittings	Operations & Maintenance - Maintenance damage	Composite	.02	.002	.001	.000

TABLE LVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
	Turbine Support Structure Cracking	Operations & Maintenance - Maintenance damage	Composite	.03	.002	.01	.001
	COMPOSITE SUBTOTAL			3.37	.257	.90	.048
TOTAL	PARTICULAR			4.32	292	1.33	.063
	COMPOSITE			4.32	.292	1.33	.063

TABLE LVIII. SUMMARIZATION OF REMEDIAL ACTIONS

GROUP: CONTROL OF DESIGN CONFIGURATION/ARRANGEMENT/MATERIALS

SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Require That the Pump Be Placed Outside Gearbox	Lubrication Pump Failures	Preliminary Design - Internal arrangement	Particular	.10	.005	-	-
			Composite	.07	.003	.03	.001
	PARTICULAR SUBTOTAL			.10	.005	-	-
	COMPOSITE SUBTOTAL			.07	.003	.03	.001
Preclude Simultaneous Precise and Gross Assembly Techniques	Improper Maintenance	Preliminary Design - Internal arrangement	Composite	.05	.002	-	-
	COMPOSITE SUBTOTAL			.05	.002	-	-
Preclude Use of Magnesium	Environmental	Preliminary Design - Material selection	Particular	.40	.020	-	-
			Composite	.11	.006	.05	.003
	PARTICULAR SUBTOTAL			.40	.020	-	-
	COMPOSITE SUBTOTAL			.11	.006	.05	.003
Preclude Use of Plastic Compressor Lining	Improper Maintenance	Preliminary Design - Material selection	Particular	.16	.012	-	-
			Composite	.07	.006	.02	.002
	PARTICULAR SUBTOTAL			.16	.012	-	-
	COMPOSITE SUBTOTAL			.07	.006	.02	.002
Use of the Most Corrosion-Resistant Materials	Improper Maintenance	Preliminary Design - Material selection	Particular	.066	.006	.02	.002
			Composite	.31	.028	.31	.028
	PARTICULAR SUBTOTAL			.066	.006	.02	.002
	COMPOSITE SUBTOTAL			.31	.028	.31	.028

TABLE LVIII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Preclude Placement of Bearings in Hot Section or Use of Differential Bearings	Bearing Spalling (Nonclassical)	Preliminary Design - Overall engine configuration	Particular	1.26	.018	-	-
			Composite	.20	.002	.06	.001
	PARTICULAR SUBTOTAL			1.26	.018	-	-
	COMPOSITE SUBTOTAL			.20	.002	.06	.001
Require That the Gas Path Be Internal to Main Casing	Improper Maintenance	Preliminary Design - Overall engine configuration	Particular	.16	.008	-	-
			Composite	.06	.003	.03	.002
	PARTICULAR SUBTOTAL			.16	.008	-	-
	COMPOSITE SUBTOTAL			.06	.003	.03	.002
Preclude Use of Rear Drive Engines	Cases, Secondary Structure Cracking	Design Execution - Overall engine configuration	Particular	3.38	.520	.13	.02
			Composite	.39	.015	-	-
	PARTICULAR SUBTOTAL			3.38	.520	.13	.02
	COMPOSITE SUBTOTAL			.39	.015	-	-
Provide Adequate Guidance for Shafts Into Bearings	Bearing Spalling (Nonclassical)	Preliminary Design - Detail design configuration	Composite	.02	.001	.02	.001
	COMPOSITE TOTAL			.02	.001	-	-
Insure That Valving in Lubrication System Precludes Pump Flooding	Lubrication Pump Failures	Preliminary Design - Detail design configuration	Particular	.60	.015	-	-
			Composite	.20	.005	.07	.001
	PARTICULAR SUBTOTAL			.60	.015	-	-
	COMPOSITE SUBTOTAL			.20	.005	.07	.001

TABLE LVIII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Specify Positive Retention	Bearing Race Rotation Displacement	Design execution analysis available, not used, not cost effective	Particular	3.10	.150	.20	.010
			Composite	.61	.032	.61	.032
	PARTICULAR SUBTOTAL			3.10	.150	.20	.010
	COMPOSITE SUBTOTAL			.61	.032	.61	.032
Utilize Elliptical Outer Race Bearings	Bearing Roller Skidding	Design execution analysis available, not used, not cost effective	Particular	2.10	.070	-	-
			Composite	.30	.013	.24	.011
	PARTICULAR SUBTOTAL			2.10	.070	-	-
	COMPOSITE SUBTOTAL			.30	.013	.24	.011
Require That the Pump Be Placed Outside Gearbox	Lubrication Pump Failures	Preliminary Design - Internal arrangement	Particular	.10	.005	-	-
			Composite	.07	.003	.03	.001
	PARTICULAR SUBTOTAL			.10	.005	-	-
	COMPOSITE SUBTOTAL			.07	.003	.03	.001
Preclude Simultaneous Precise and Gross Assembly Techniques	Improper Maintenance	Preliminary Design - Internal arrangement	Composite	.05	.002	-	-
	COMPOSITE SUBTOTAL			.05	.002	.05	.00[illegible]
Preclude Use of Magnesium	Environmental	Preliminary Design - Material selection	Particular	.40	.020	-	-
			Composite	.11	.006	.05	.003
	PARTICULAR SUBTOTAL			.40	.020	-	-
	COMPOSITE SUBTOTAL			.11	.006	.05	.003

TABLE LVIII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Preclude Integrally Cast Blade/ Disc in Compressor	Compressor Blade/Disc Fatigue	Preliminary Design - Manufacturing approach	Particular	.40	.002	-	-
			Composite	.15	.001	.15	.001
	PARTICULAR SUBTOTAL			.40	.002	-	-
	COMPOSITE SUBTOTAL			.15	.001	.15	.001
Require Electrical Torquemeter	High-Speed Torquemeter	Preliminary Design - Design concept	Particular	5.83	.222	-	-
			Composite	1.13	.043	1.13	.043
	PARTICULAR SUBTOTAL			5.83	.222	-	-
	COMPOSITE SUBTOTAL			1.13	.043	1.13	.043
TOTAL	PARTICULAR			19.43	1.101	.42	.035
	COMPOSITE			3.75	.164	3.19	.146

TABLE LIX. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: ANALYTICAL PROCEDURES
SUBGROUP: IMPLEMENTATION OF IMPROVED DESIGN PRACTICES

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Further Analysis of the Effects of Aircraft Equipment and Installation on the Airframe	Airframe Related	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	2.56	160	-	-
			Composite	.76	.046	.29	.017
	PARTICULAR SUBTOTAL			2.56	.160	-	-
	COMPOSITE SUBTOTAL			.76	.046	.29	.017
Increase Analysis To Encompass Bearing Spacer Restraint	Accessory	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.36	.010	.12	.004
	COMPOSITE SUBTOTAL			.36	.010	.12	.004
Increased Analysis Search for Potential Race Rotation and/or Displacement	Bearing Race Rotation Displacement	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	2.40	.120	-	-
			Composite	.16	.009	.08	.005
	PARTICULAR SUBTOTAL			2.40	.120	-	-
	COMPOSITE SUBTOTAL			.16	.009	.08	.005
Further Consideration of Engine/Protection Screen Interfaces	Foreign-Object Damage	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.10	.006	.04	.002
	COMPOSITE SUBTOTAL			.10	.006	.04	.002

TABLE LIX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Increase Concentration in the Area of Outer Race Retention	Power Train Reduction	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.07	.001	.03	.001
	COMPOSITE SUBTOTAL			.07	.001	.03	.001
TOTAL (SUBGROUP)	PARTICULAR			5.49	.297	.29	.007
	COMPOSITE			1.45	.072	.66	.029

TABLE LX. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: ANALYTICAL PROCEDURES
SUBGROUP: CONSIDERATION OF NORMAL CONDITIONS

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Intensify Analysis as Related to Potential Resonant Condition	Compressor Blade/Disc Fatigue	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	2.10	.005	.72	.002
			Composite	.23	.001	.12	.000
	PARTICULAR SUBTOTAL			2.10	.005	.72	.002
	COMPOSITE SUBTOTAL			.23	.001	.12	.000
Investigate Thermal Effects of Expansion Rates and Its Effect on Bearing Loads	Bearing Cage Wearing, Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	.68	.025	-	-
			Composite	.07	.002	.05	.001
	PARTICULAR SUBTOTAL			.68	.025	-	-
	COMPOSITE SUBTOTAL			.07	.002	.05	.001
Increase Emphasis on Low-Cycle Fatigue and Potential Resonance	Turbine Blade/Wheel Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.05	.001	.02	.000
	COMPOSITE SUBTOTAL			.05	.001	.02	.000
Analyze More Intensely the Loads Arising From External Drive Shafting	Turbine Support Structure	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.05	.02	.01	.001
	COMPOSITE SUBTOTAL			.05	.02	.01	.001

TABLE LX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Give Increased Consideration to the Vibrational Effect on Riveted Assembly	Cases, Secondary Structure Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.50	.060	-	-
			Composite	.04	.002	02	.001
	PARTICULAR SUBTOTAL			1.50	.060	-	-
	COMPOSITE SUBTOTAL			.04	.002	.02	.001
Increase Analysis Concerning Material Selection and Effect of Erosion on Fatigue Strength	Compressor Vane Erosion	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	.32	.008	-	-
			Composite	.03	.001	.012	.000
	PARTICULAR SUBTOTAL			.32	.008	-	-
	COMPOSITE SUBTOTAL			.03	.001	.012	.000
Increase Consideration of Aircraft Vibrations on Tail Pipe Mounting	Exhaust	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.01	.000	.00	.000
	COMPOSITE SUBTOTAL			.01	.000	.00	.000
TOTAL (SUBGROUP)	PARTICULAR			4.71	.119	.75	.003
	COMPOSITE			.48	.027	.23	.003

TABLE LX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Increase Consideration of Real Maintenance Environment	Fuel Control Failures	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.30	.009	.12	.003
	COMPOSITE SUBTOTAL			.30	.009	.12	.003
Consider Combinations and Sequencing of Failures in Lube System Design	Lubrication Pump Failures	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.50	.050	.36	.010
			Composite	.11	.003	.03	.001
	PARTICULAR SUBTOTAL			1.50	.050	.36	.010
	COMPOSITE SUBTOTAL			.11	.003	.03	.001
Additional Analysis of Potential Operator Techniques	Operator Induced	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.10	.005	.04	.002
	COMPOSITE SUBTOTAL			.10	.005	.04	.002
Analyze the Possible Damage of Parts due to Maintenance	High-Speed Torquemeter	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	.88	.030	-	-
			Composite	.10	.005	.04	.002
	PARTICULAR SUBTOTAL			.88	.030	-	-
	COMPOSITE SUBTOTAL			.10	.005	.04	.002

TABLE LX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Engine Baseline	Potential Benefit Maximum Index	Maximum UER	Minimum Index	Minimum UER
Consider Combinations and Sequences in Lube System Design	Lubrication Filters Coolers	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	.70	.010	-	-
			Composite	.09	.002	.03	.000
	PARTICULAR SUBTOTAL			.70	.010	-	-
	COMPOSITE SUBTOTAL			.09	.002	.03	.000
Murphy-Proof Existing Arrangements	Improper Maintenance	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.08	.005	.01	.001
	COMPOSITE SUBTOTAL			.08	.005	.01	.001
Consider Effect of Tolerance Buildup	Combustion Swirl Cup	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	1.20	.040	.30	.010
			Composite	.08	.003	.02	.001
	PARTICULAR SUBTOTAL			1.20	.040	.30	.010
	COMPOSITE SUBTOTAL			.08	.003	.02	.001
Consider Subsequent Manufacturing Operations and Maintenance Damage in Calculating Stress	Combustion Housing Corrosion Fittings	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	2.[illegible]2	.080	-	-
			Composite	.05	.001	.01	.000
	PARTICULAR SUBTOTAL			2.52	.080	-	-
	COMPOSITE SUBTOTAL			.05	.001	.01	.000

TABLE LX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Increased Analytical Procedures Concerning Shaft Misalignment and Unbalance	Turbine Shaft Couplings	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.04	.001	.00	.000
	COMPOSITE SUBTOTAL			.04	.001	.00	.000
Further Consideration of Deflections in Assembly due to Thermal Growth and Air Pressure	Compressor Diffuser Cracking	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.02	.001	.01	.000
	COMPOSITE SUBTOTAL			.02	.001	.01	.000

TABLE LX - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Further Investigation and Design Analysis Concerning Flatness of Runner, Oil Scavenge, and Bellows at Natural Frequency	Carbon Seal Leakage	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Particular	6.12	.360	-	-
			Composite	.14	.009	.04	.002
	PARTICULAR SUBTOTAL			6.12	.360	-	-
	COMPOSITE SUBTOTAL			.14	.009	.04	.002
Analysis of Oil Flow Characteristics, Roller End Radius, Spline Lockup Effects, and Jet Size Blockage Potential	Bearing Spalling (Nonclassical)	Design Execution - Analysis available, not used, reasonable cost, reasonable effectiveness	Composite	.12	.002	.05	.001
	COMPOSITE SUBTOTAL			.12	.002	.05	.001
TOTAL (SUBGROUP)	PARTICULAR			13.58	.603	.89	.027
	COMPOSITE			1.23	.046	.40	.013
TOTAL (GROUP)	PARTICULAR			23.78	1.019	1.93	.037
	COMPOSITE			3.16	.145	1.29	.045

TABLE LXI. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: DECREASE IN FUNCTIONAL REQUIREMENTS
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Eliminate Requirement for Power Management System	Fuel Control Failure	Specifications & Requirements - Requirement for features	Particular	9.70	.210	2.76	.060
			Composite	1.48	.032	.88	.019
	PARTICULAR SUBTOTAL			9.70	.210	2.76	.060
	COMPOSITE SUBTOTAL			1.48	.032	.88	.019
Eliminate Requirement for High-Speed Output	Torquemeter	Specifications & Requiremenrs - Program schedule	Particular	5.91	.225	.05	.002
			Composite	1.14	.043	1.14	.043
	PARTICULAR SUBTOTAL			5.91	.225	.05	.002
	COMPOSITE SUBTOTAL			1.14	.043	1.14	.043
TOTAL	PARTICULAR			15.61	.435	2.81	.062
	COMPOSITE			2.62	.075	2.02	.062

TABLE LXII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: IMPROVED LOGISTICS MANAGEMENT PROGRAM
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Improved Logistics Management Program	Convenience	Operations & Maintenance - Optimum logistics management program not utilized	Particular	13.20	1.200	-	-
			Composite	2.20	.200	2.20	.200
	PARTICULAR SUBTOTAL			13.20	1.200	-	-
	COMPOSITE SUBTOTAL			2.20	.200	2.20	.200
TOTAL	PARTICULAR			13.20	1.200	-	-
	COMPOSITE			2.20	.200	2.20	.200

TABLE LXIII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: EMPHASIS ON R&M IN REQUIREMENTS
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Additional Consideration Should Be Given to Maintenance Durability	Improper Maintenance	Specifications & Requirements - Lack of aggressive R&M	Particular	2.55	.150	.35	.020
			Composite	.85	.050	.17	.010
	PARTICULAR SUBTOTAL			2.55	.150	.35	.020
	COMPOSITE SUBTOTAL			.85	.050	.17	.010
Require Higher Lives on Gearbox Bearings and Seals	Power Train Reduction	Specifications & Requirements - Lack of aggressive R&M	Particular	.39	.007	.05	.001
			Composite	.20	.004	.05	.001
	PARTICULAR SUBTOTAL			.39	.007	.05	.001
	COMPOSITE SUBTOTAL			.20	.004	.05	.001
Give More Consideration to Helicopter Environment	Combustion Housing Corrosion & Fittings	Specifications & Requirements - Lack of aggressive R&M	Particular	1.45	.05	.00	.000
			Composite	.20	.007	.05	.002
	Exhaust	Specifications & Requirements - Lack of aggressive R&M	Particular	.35	.003	.03	.000
			Composite	.19	.002	.10	.001
	PARTICULAR SUBTOTAL			1.80	.053	.03	.000
	COMPOSITE SUBTOTAL			.39	.009	.15	.003
Require Higher B_{10} Lives	Bearing Classical Spalling	Specifications & Requirements - Lack of aggressive R&M	Particular	1.40	.025	.00	.000
			Composite	.18	.003	.12	.002
	PARTICULAR SUBTOTAL			1.40	.025	.00	.000
	COMPOSITE SUBTOTAL			.18	.003	.12	.002

TABLE LXIII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Greater Consideration of Operations on Engine and/or Aircraft	Operator Induced	Specifications & Requirements - Lack of aggressive R&M	Particular	.42	.020	.08	.004
			Composite	.25	.012	.10	.005
	PARTICULAR SUBTOTAL			.42	.020	.08	.004
	COMPOSITE SUBTOTAL			.25	.012	.10	.005
TOTAL	PARTICULAR			6.56	.255	.51	.025
	COMPOSITE			1.87	.078	.59	.021

TABLE LXIV. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: PROVIDE GREATER FLEXIBILITY IN SCHEDULING
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Allow Adequate Time for Configuration Changes in Growth	Compressor Blade/Disc Fatigue	Specifications & Requirements - Program schedule	Particular	2.10	.005	1.30	.003
			Composite	.74	.002	.20	.001
	PARTICULAR SUBTOTAL			2.10	.005	1.30	.003
	COMPOSITE SUBTOTAL			.74	.002	.20	.001
Allow Adequate Time for Development of Casting and Tooling for Integrally Cast Nozzles	Turbine Nozzle Band Cracking	Specifications & Requirements - Program schedule	Particular	1.50	.042	.07	.002
			Composite	.52	.014	.11	.005
	PARTICULAR SUBTOTAL			1.50	.042	.07	.002
	COMPOSITE SUBTOTAL			.52	.014	.11	.005
TOTAL	PARTICULAR			3.60	.047	1.37	.005
	COMPOSITE			1.26	.016	.31	.006

TABLE LXV. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: ADDITIONAL CONTROL OF ENGINE/AIRFRAME INTERFACE
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UFR
Specify Accessibility to All Accessories	Fuel Control Failures	Preliminary Design - Engine/airframe interface	Particular	5.87	.13	-	-
			Composite	.38	.006	.13	.002
	Improper Maintenance	Preliminary Design - Engine/airframe interface	Particular	.15	.007	-	-
			Composite	.06	.003	.03	.000
	Airframe Related	Preliminary Design - Engine/airframe interface	Particular	.64	.040	.08	.005
			Composite	.23	.015	.04	.003
	Electrical Ignition	Design Execution - Analysis available not used, reasonable cost, reasonable effectiveness	Particular	-		-	-
			Composite	.06	.002	.01	.000
	PARTICULAR SUBTOTAL			6.66	.177	.08	.005
	COMPOSITE SUBTOTAL			.73	.026	.21	.005
Specify Engine Control Protection Devices	Operator Induced	Preliminary Design - Engine/airframe interface	Particular	1.20	.060	.20	.010
			Composite	.12	.006	.020	.001
	PARTICULAR SUBTOTAL			1.20	.060	.20	.01
	COMPOSITE SUBTOTAL			.12	.006	.020	.001
Specify Close Location of the Protective Screen to Engine Inlet	Foreign-Object Damage	Preliminary Design - Engine/airframe interface	Particular	.14	.008	-	-
			Composite	.20	.013	.10	.006
	PARTICULAR SUBTOTAL			.14	.008	-	-
	COMPOSITE SUBTOTAL			.20	.013	.10	.006

TABLE LXV - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Specify Pod-Mounted Engines	Erosion	Preliminary Design - Engine/airframe interface	Particular	20.71	1.000	.21	.010
			Composite	.15	.007	.10	.005
	PARTICULAR SUBTOTAL			20.71	1.000	.21	.010
	COMPOSITE SUBTOTAL			.15	.007	.10	.005
TOTAL	PARTICULAR			28.71	1.245	.49	.025
	COMPOSITE			1.20	.052	.43	.017

TABLE LXVI. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: DE-EMPHASIS ON ACQUISITION COST
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Preclude Use of Pneumatic Fuel Control	Fuel Control Failure	Specifications & Requirements - Acquisition cost emphasis	Particular	8.28	.180	3.50	.075
		Preliminary Design - Design concept	Composite	.56	.012	.35	.008
	PARTICULAR SUBTOTAL			8.28	.180	3.50	.075
	COMPOSITE SUBTOTAL			.56	.012	.35	.008
Require Integrally Cast Assembly	Turbine Nozzle and Band Cracking	Specifications & Requirements - Acquisition cost emphasis	Particular	1.50	.042	.07	.002
			Composite	.52	.014	.11	.005
	PARTICULAR SUBTOTAL			1.50	.042	.07	.002
	COMPOSITE SUBTOTAL			.52	.014	.11	.005
TOTAL	PARTICULAR			9.78	.222	3.57	.077
	COMPOSITE			2.62	.075	2.02	.062

TABLE LXVII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: ADDITIONAL QUALITY CONTROL EFFORT
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Improve Quality Control of Assy Procedures	Improper Maintenance	Manufacturing & Quality Control - Optimum assembly/Q.C. procedures not utilized	Composite	.12	.007	.06	.003
	COMPOSITE SUBTOTAL			.12	.007	.06	.003
Improve Quality Control Procedures of Auxiliary Gearbox Onto Engine	Accessory	Manufacturing & Quality Control - Optimum assembly/Q.C. procedures not utilized	Composite	.09	.003	.06	.002
	COMPOSITE SUBTOTAL			.09	.003	.06	.002
Assembly of Seal Onto Housing Should Include Intensified Quality Control	Carbon Seal Leakage	Manufacturing & Quality Control - Optimum assembly/Q.C. procedures not utilized	Composite	.05	.002	.02	.001
	COMPOSITE SUBTOTAL			.05	.002	.02	.001
Assembly of Snap Ring Into Slot Should Include Intensified Quality Control	Bearing Race Rotation Displacement	Manufacturing & Quality Control - Optimum assembly/Q.C. procedures not utilized	Composite	.03	.001	.02	.000
	COMPOSITE SUBTOTAL			.03	.001	.02	.000

TABLE LXVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Additional Quality Control of Detail Material Properties and Manufacturing Variations	Accessory	Manufacturing & Quality Control - Failure to follow specifications	Composite	.02	.001	.01	.000
	Bearing Spalling (Nonclassical)	Manufacturing & Quality Control - Failure to follow specifications	Composite	.14	.003	.07	.001
	Turbine Support Structure Cracking	Manufacturing & Quality Control - Failure to follow specifications	Composite	.08	.004	.05	.002
	Power Train Reduction	Manufacturing & Quality Control - Failure to follow specifications	Composite	.04	.001	.02	.000
	Carbon Seal Leakage	Manufacturing & Quality Control - Failure to follow specifications	Composite	.05	.014	.03	.002
	Lubrication System Miscellaneous	Manufacturing & Quality Control - Failure to follow specifications	Composite	.03	.001	.01	.000
	Air Valve Binding, Leaking	Manufacturing & Quality Control - Failure to follow specifications	Composite	.02	.001	.01	.000
	Combustion Housing Corrosion	Manufacturing & Quality Control - Failure to follow specifications	Composite	.01	.001	.01	.000

TABLE LXVII - Continued

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
	Bearing Cage Wear, Cracking	Manufacturing & Quality Control - Failure to follow specifications	Composite	.01	.001	.01	.000
	Combustion Swirl Cup Problems	Manufacturing & Quality Control - Failure to follow specifications	Composite	.03	.001	.02	.001
			Particular	1.35	.045	.90	.030
	PARTICULAR SUBTOTAL			1.75	.072	1.12	.035
	COMPOSITE SUBTOTAL			.43	.028	.24	.006
TOTAL	**PARTICULAR**			2.04	.085	1.28	.041
	COMPOSITE			.72	.041	.40	.012

TABLE LXVIII. SUMMARIZATION OF REMEDIAL ACTIONS
GROUP: CLOSER CONTROL OF OPERATION OF ENGINE
SUBGROUP:

Description of Remedial Action	Failure Modes Affected	Causal Factor Source	Potential Benefit				
			Engine Baseline	Maximum		Minimum	
				Index	UER	Index	UER
Enlist Procedures To Prevent Hot Starts, Erroneous Removals for Low-Power Overstress, Overtorque	Operator Induced	Operation & Maintenance - Avoidable operation of engine outside limits	Composite	.57	.030	.19	.010
	COMPOSITE SUBTOTAL			.57	.030	.19	.010
Reduce Operation of Engine Under Severe Conditions	Erosion	Operation & Maintenance - Avoidable operation of engine outside limits	Composite	.10	.005	.05	.002
	COMPOSITE SUBTOTAL			.10	.005	.05	.002
Adhere to Engine Shutdown Procedures	Bearing Spalling (Nonclassical)	Operation & Maintenance -Avoidable operation of engine outside limits	Particular	1.68	.042	.72	.018
			Composite	.03	.001	.01	.000
	PARTICULAR SUBTOTAL			1.68	.042	.72	.018
	COMPOSITE SUBTOTAL			.03	.001	.01	.000
TOTAL	PARTICULAR			2.35	.077	.96	.030
	COMPOSITE			.70	.036	.25	.012